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NSWC TECHNICAL REPORT

WHITE OAK LABORATORY

MECHANICAL DAMAGE TO LMFBR STRUCTURES FROM A SEVERE CDA. SUMMARY REPORT OF WORK ACCOMPLISHED IN FY 76

BY
Richard A. Lorenz

8 FEBRUARY 1977

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During FY 76 a study was undertaken to analyze the response of the Clinch River Breeder Reactor (CRBR) primary containment system to three specific Core Disruptive Accidents (CDAs). These CDAs are represented by core energetics of 300, 661, and 1200 MJ when expanded to one atmosphere (1.01×10^5Pa). In particular the response of the reactor vessel closure headshear ring structural system to the CDA loadings was analyzed. Details of the hydrodynamic and structural analyses are presented in an appendix.

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20. ABSTRACT (Cont'd)

Preliminary results of an analysis of the structural response of the CRBR outlet piping elbow to CDA loadings are given. Other work performed as a part of a general consulting service to NRC is summarized in the text.

NSWC/WOL/TR 76-162 8 February 1977

MECHANICAL DAMAGE TO LMFBR STRUCTURES FROM A SEVERE CDA. SUMMARY REPORT OF WORK ACCOMPLISHED IN FY 76.

The work described in this report was performed under the sponsorship of the Liquid Metal Fast Breeder Reactor (LMFBR) Branch, Division of Project Management, Nuclear Regulatory Commission during the period July 1975-June 1976 (NRC Contract No. AT(49-24)-0103). The primary objective of this task is to provide consultive services to the Nuclear Regulatory Commission in their evaluation of the mechanical damage that could occur in an LMFBR from a severe Core Disruptive Accident (CDA).

The author wishes to acknowledge the expert advice and assistance of A. Kushner of the Explosion Dynamics Branch who guided the shear ring structural analysis and who also performed the bulk of the related work. The author also wishes to acknowledge the work of M. Giltrud of the Explosion Dynamics Branch who is currently developing the computer models needed to analyze the structural response of the outlet piping elbow to CDA loadings.

Julius W. Enig

JULIUS W. ENIG
By direction

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ILLUSTRATIONS (CONT'D)

SUMMARY AND CONCLUSIONS

This report describes the work performed by the Naval Surface Weapons Center, White Oak Laboratory (NSWC/WOL) during FY 76 for the Nuclear Regulatory Commission (NRC) under Contract No. AT(49-24)-0103, Modification 14.

Approximately 1.2 professional man-years were expended in FY 76. The major effort was directed toward an assessment of the mechanical damage to the primary containment boundary of the Clinch River Breeder Reactor (CRBR) when subjected to severe Core Disruptive Accident (CDA) loadings. This mechanical damage analysis was performed to support the NRC staff in their review of Appendix F (CDA Accommodation) in the CRBR Preliminary Safety Analysis Report (PSAR).

We used a modified version of the PSAR CRBR computer model in our REXCO-HEP hydrodynamic calculations. The main differences between the two computer models is that, in the NSWC/WOL version, the Lagrangian mesh is coarser, the core support cone is modeled more realistically, and the gaps between the rotating plugs and their corresponding shear rings are accounted for. REXCO-HEP hydrodynamic calculations were made for a 300 MJ CDA supplied by the NRC staff, the 661 MJ CDA specified in Appendix F of the CRBR PSAR, and a 1200 MJ CDA supplied by the NRC staff.

A finite element model of the CRBR large rotating plug (LRP) shear ring structural system was developed. We then performed a dynamic nonlinear inelastic structural analysis of the LRP shear ring using the REXCO-HEP generated loading histories on the reactor head cover as forcing functions. Our analysis showed that the current PSAR shear ring design is capable of withstanding the 300 MJ CDA but will fail under the 661 MJ and 1200 MJ CDA loadings. In view of these predicted failures, we investigated a holddown concept for the rotating plugs which would serve the purpose for which the shear rings were intended. Preliminary investigations of this concept indicate that it could serve as the basis for the design of a head containment system capable of withstanding the 1200 MJ CDA loading.

A finite element model of the CRBR outlet piping elbow was constructed and a static linear elastic structural analysis was performed. The analysis showed that plastic regions will form in the elbow under the CDA pressure levels calculated by REXCO-

HEP. Further analysis of the piping elbows will be carried out using a computer code capable of performing static and dynamic non-linear inelastic structural analyses of arbitrary shells.

Preliminary analyses performed so far indicate that the weakest structural components in the CRBR primary containment system are the rotating plug shear rings, the reactor support ledge, the inlet and outlet piping nozzles and elbows, and the head-mounted components.

We support the position that model experiments are needed to demonstrate the structural integrity and leak retention capability of the reactor head cover under CDA loading conditions. These experiments should be modeled to a sufficient scale to give meaningful results.

BACKGROUND

From 1956 to 1964, the Naval Surface Weapons Center, White Oak Laboratory, (NSWC/WOL, formerly Naval Ordnance Laboratory) was engaged in an extensive research program for the Energy Research and Development Administration (ERDA, formerly Atomic Energy Commission). This program was directed to the study of reactor vessel response to severe core disruptive accidents (CDAs). With this background and a background in the general area of response of structures to dynamic and explosive loadings, NSWC/WOL has provided consultive services to the Nuclear Regulatory Commission (NRC, formerly Atomic Energy Commission) in this area since 1965.

With the current emphasis on liquid metal fast breeder reactors (LMFBRs), the NRC has increased its effort in safety analyses that have relevance to license applications. To assist in this increased effort, the NRC is taking full advantage of their consultants by assigning general evaluation tasks in accordance with the particular expertise of the consultant. NSWC/WOL has been requested to analyze the mechanical damage to LMFBR structures from severe CDA loads. In addition NRC has asked NSWC/WOL to evaluate certain mechanical response computer codes developed by ERDA laboratories and private industry for the safety analysis of LMFBRs.

INTRODUCTION

The schematic of a typical LMFBR is shown in Figure 1. During a CDA, a large amount of energy is released in a relatively short time in the reactor core region. The resulting high pressure distorts the surrounding structures and accelerates the coolant in the outlet plenum. The coolant slug moves upward and impacts the reactor head cover (rotating plugs in Fig. 1). Pressure pulses travel down the inlet and outlet piping and interact with the primary piping components.

The REXCO-HEP computer code calculates the hydrodynamic pressure propagation through the reactor internals, the motion of the coolant slug, the time-dependent loading histories on the reactor structures, and the gross deformation of the reactor vessel and structures surrounding the core. REXCO-HEP is a two-dimensional axially-symmetric Lagrangian hydrocode which can accommodate elastic-plastic regions and in which thin vessels

(e.g., reactor vessel and core barrel) can be modeled as thin shell sections. CDA energetics are input to a REXCO-HEP calculation in the form of a pressure vs. volume expansion curve for the core region.

The response of any particular reactor structure to CDA loads is determined by applying the REXCO-HEP generated loads to an appropriate mathematical or computer model of the structure. The complexity of the model used will depend strongly upon the complexity of the structure itself and on the loading conditions involved. During an analysis, the stress and/or strain histories are calculated while the structural component is being subjected to the CDA loads. An assessment of these stress and strain histories is then made to determine whether or not the component would fail under the applied loading.

OBJECTIVE

The objective of our work is to provide the NRC with an assessment of the probable mechanical damage suffered by LMFBR structures when subjected to CDA generated loads. We are concerned in particular with the primary coolant boundary (e.g., reactor vessel, reactor head cover, head-mounted components, primary piping, and primary piping components), the core support structures (e.g., core barrel, core support plate, and core support cone), and the reactor support structures (e.g., reactor hold-down bolts and main support ledge). It is imperative that these structures remain intact during a CDA in order that the radioactive core materials can be contained and cooled following the accident.

As noted in the Introduction, the results of a REXCO-HEP calculation provide the loading conditions for all subsequent structural analyses concerning the LMFBR primary containment boundary and support structures. In view of this unique and vital role played by REXCO-HEP in the safety analysis of LMFBRs, NRC has requested us to evaluate the REXCO-HEP code and to maintain the most recent version of the code in active status on the NSWC/WOL computer where it can be used in our CDA analyses.

Task 1. Consultive Services

Essentially the entire NSWC/WOL effort in FY 76 has been directed toward assisting the NRC staff in their review of the Clinch River Breeder Reactor (CRBR) Preliminary Safety Analysis Report (PSAR) (ref. (1)). Particular emphasis was placed on the

1. (No author), "Clinch River Breeder Reactor Project Preliminary Safety Analysis Report," Project Management Corporation, April 1975.

evaluation of the applicant's structural analysis of the primary containment boundary presented in Appendix F of the PSAR, "Core Disruptive Accident Accommodation." Questions which have arisen in the course of our review and requests for additional information have been formally presented to the applicant by NRC. Specific structures and components that we have analyzed in detail will be discussed under Task 3.

We have stressed the need for model experiments to demonstrate the structural integrity and leak retention capability of the CRBR reactor head cover under CDA loading conditions. The asymmetries in the geometric configuration and in the loading history of the head have not been adequately modeled in the analytical calculations performed to date. Figure 1 shows a schematic diagram of the CRBR. The geometric asymmetries result from the non-concentric rotating plugs which comprise the reactor head cover, and from the asymmetrical distribution of the head-mounted components. A top view of the head is shown in Figure 2. Inaccuracies arise in the REXCO-HEP calculated loading history on the head because the Upper Internals Structure (UIS) is not included in the REXCO-HEP computer model. The UIS is located directly above the core, as shown in Figure 1, and should absorb much of the energy imparted to the sodium slug in a REXCO-HEP calculation. A more detailed view of the UIS is given in Figure 3. The loading on the UIS is then transferred to the intermediate rotating plug through the four UIS support columns. Thus the rotating plugs are initially loaded asymmetrically. To complicate matters, the UIS support columns may buckle. When the sodium slug finally does hit the head, it is not clear that the rotating plugs will seat themselves without damage against the shear rings and form a barrier to sodium leakage into the head compartment. For these reasons it is felt that experimental tests are required in which the rotating plugs, the head-mounted components, and the UIS are properly modeled to a sufficient scale to give meaningful results.

We assisted the NRC staff in preparing their response to the third set of interrogatories (ref. (2)) by the Natural Resources Defense Council concerning the REXCO-HEP computer code.

Frequent meetings were held with the NRC staff in Bethesda, MD, to discuss various matters related to the mechanical damage of the CRBR from CDA loadings. Primarily, the damage analysis described under Task 3 in this report was presented and discussed.

Task 2. Computer Code Maintenance and Evaluation

A new version of the REXCO-HEP code, Release 3A, and the associated REZONE code, Release 1, were received from Argonne

2. (No author), "Third Set of Iterrogatories to the Nuclear Regulatory Commission Staff," Natural Resources Defense Council, Docket No. 50-537, 2 January 1976.

National Laboratory (ANL) in May 1975 and have been converted and activated on the NSWC/WOL CDC 6500 computer. Although the basic hydrodynamic and elastic-plastic calculations in REXCO-HEP have remained essentially the same as reported in reference (3), the thin vessel calculations have been expanded and completely changed. Because of the priority of the review of Appendix F in the CRBR PSAR, only a limited amount of progress was made during FY 76 in reviewing the theory and programming of these new thin vessel calculations.

The older version of the REXCO-HEP code, Release 1, which has already been evaluated in reference (3), continues to be maintained and used as the working version of REXCO-HEP at NSWC/WOL.

The discrepancy we noted (ref (4)) between an ANL CRBR PSAR REXCO-HEP run and a NSWC/WOL REXCO-HEP run has been resolved (Both runs were made with Release 1 versions of the code). As noted in ANL's reply (ref. (5)) this discrepancy was due to a motion restriction factor programmed into the code. If the calculated change in velocity of a mesh point during any timestep was less than the value of the motion restriction factor, the velocity of that mesh point remained unchanged. While converting Release 1 of the REXCO-HEP code to the NSWC/WOL computer, we saw no physical need for this motion restriction factor and essentially eliminated it. When the same motion restriction factor is used, the ANL and the NSWC/WOL results are in satisfactory agreement. The motion restriction factor was initially introduced to avoid computational difficulties. Since these computational difficulties no longer exist, we recommend that use of this motion restriction factor be discontinued.

Task 3. Mechanical Damage Analysis

The mechanical damage analysis performed in FY 76 was done in support of the review of Appendix F in the CRBR PSAR.

Hydrodynamic Calculations. The CRBR computer model used in the NSWC/WOL REXCO-HEP calculations is shown in Figure 4. This figure represents the Lagrangian grid for a two-dimensional axially-symmetric finite difference hydrodynamic calculation by the REXCO-HEP code. The main differences between the NSWC/WOL model and the model presented in Section D.6 of the PSAR are as

3. R. A. Lorenz, "Evaluation of the REXCO-H and REXCO-HEP Reactor Excursion Containment Codes," NOLTR 74-63, 14 March 1975.
4. NSWC/WOL Letter 241:RAL:fh, 10462, SER: 2334, R. A. Lorenz to Y. W. Chang, dated 25 April 1975.
5. ANL Letter, Y. W. Chang to R. A. Lorenz, dated 8 August 1975.

follows: The NSWC/WOL Lagrangian mesh is coarser; this allows us to use a larger timestep thereby keeping the total running time for a problem down to a reasonable length on our CDC 6500 computer. In addition, the coarser mesh does not distort as quickly as a finer mesh would, enabling us to continue a REXCO-HEP calculation to reasonably long times without the need to rezone the mesh. The core support cone is modeled more realistically in the NSWC/WOL model, resulting in higher calculated pressures in the inlet plenum than those calculated using the PSAR model. The reactor head cover is allowed to move upward a short distance before the holddown bolts begin to restrain it, in order to represent a nominal 1/4 inch (0.635 cm) gap between each rotating plug and its corresponding shear ring.

The energetics of a CDA are represented by the P-V expansion curve of the vaporized core materials. The three basic CDAs for which REXCO-HEP calculations were made are: a 300 MJ CDA supplied by the NRC staff, the 661 MJ CDA specified in Appendix F of the CRBR PSAR, and a 1200 MJ CDA supplied by the NRC staff. The P-V expansion curves for these CDAs are shown in Figure 5 and the values used to represent these curves in the REXCO-HEP calculations are given in Tables 1 through 3.

The REXCO-HEP calculations were continued through t = 160 msec for the 300 MJ and 661 MJ CDAs, and through t = 135 msec for the 1200 MJ CDA. By these times, the major damage to the reactor structures has occurred and the pressure pulses are only reverberating throughout the reactor system. In an actual CDA the viscous effects, ignored by REXCO-HEP, will be damping out these oscillations. At the same time, localized mesh distortion is becoming significant in the region near the top of the core barrel so that further computation would soon become meaningless. Selected values from the REXCO-HEP calculations are presented in Tables 4 through 7.

<u>LRP Shear Ring</u>. A detailed study was undertaken to analyze the structural response of the large rotating plug (LRP) shear ring under CDA loads. The analysis presented in Appendix F of the CRBR PSAR and our own preliminary calculations point to the LRP shear ring as being one of the critical components in maintaining the structural integrity of the reactor head cover. A detailed discussion of our analysis of the LRP shear ring is presented in Appendix A. The REXCO-HEP generated CDA loading histories on the reactor head cover are applied to a finite element structural model of the head and LRP shear ring. Our analysis of the current shear ring design indicates that the LRP shear ring is capable of withstanding the 300 MJ CDA but will fail under the 661 MJ and 1200 MJ CDA loadings. In view of these predicted failures, we investigated a hold-down concept for the rotating plugs which would serve the purpose for which the shear rings were intended. Preliminary investigations of this concept

indicate that it could serve as the basis for the design of a head containment system capable of withstanding the 1200 MJ CDA loading.

Outlet Piping Elbow. A finite element model of the CRBR outlet piping elbow was constructed using triangular plate elements. The influence of false bending stresses due to the modeling of the toroidal elbow section with triangular flat plate elements was examined and found to be negligible. The outlet piping elbow is made of Type 316 stainless steel and has a 36 inch (91.4 cm) outer diameter, a 54 inch (137 cm) radius of curvature, and a 0.5 inch (1.27 cm) thickness. A static linear elastic structural analysis was performed using the NASTRAN finite element computer code with a static uniform pressure of 100 psi (0.690 MPa) applied to the elbow model. An elastic modulus of 22.4×10^6 psi (1.54×10^{11} Pa) and a Poisson's ratio of 0.33 were used in the analysis. These properties correspond to Type 316 stainless steel at 1000°F (538°C).

Type 316 stainless steel at 1000°F (538°C) has a static yield stress of 18 Ksi (124 MPa) and an ultimate stress of 68 Ksi (469 MPa). Scaling the results of the linear elastic calculation indicates that the outlet piping elbow will yield at a static pressure of 450 psi (3.10 MPa). If we assume that the maximum allowable stress is 0.7 times the ultimate stress, then the outlet piping elbow may be considered safe under static pressures less than 1200 psi (8.28 MPa).

Because the peak pressures calculated by REXCO-HEP in the region of the outlet piping nozzle exceed 450 psi (3.10 MPa) for the 300 MJ, 661 MJ and 1200 MJ CDAs, regions of plastic deformation are expected to occur within the elbow and NASTRAN will not be capable of performing the analysis. We expect to use the STAGS finite difference computer code for a more complete nonlinear static and dynamic analysis of both the inlet and outlet piping elbows. STAGS is capable of performing static and dynamic structural analyses of arbitrary shells where the nonlinear effects caused by finite deflections and material elastic-plastic behavior are accounted for.

Critical Components. The structural analysis presented in Appendix F of the CRBR PSAR and our own structural analysis performed so far together indicate that the weakest components in the CRBR primary containment system are the rotating plug shear rings, the reactor support ledge, the input and output piping nozzles and elbows, and the head-mounted components. More thorough structural analyses of these components will be performed as more complete design information becomes available.

REFERENCES

1. (No author), "Clinch River Breeder Reactor Project Preliminary Safety Analysis Report," Project Management Corporation, April 1975.

2. (No author), "Third Set of Iterrogatories to the Nuclear Regulatory Commission Staff," Natural Resources Defense Council, Docket No. 50-537, 2 January 1976.

3. R. A. Lorenz, "Evaluation of the REXCO-H and REXCO-HEP Reactor Excursion Containment Codes," NOLTR 74-63, 14 March 1975.

4. NSWC/WOL Letter 241:RAL:fh, 10462, SER: 2334, R. A. Lorenz to Y. W. Chang, dated 25 April 1975.

5. ANL Letter, Y. W. Chang to R. A. Lorenz, dated 8 August 1975.

Table 1

Core Pressure-Volume Relationship
for the 300 MJ CDA

Pressure (MPa)*	Volume (V/Vo)**
7.599	1.00
5.066	1.04
3.040	1.93
2.027	4.33
1.013	16.53
0.507	52.03
0.101	413.4

* 1 MPa = 10 bars = 9.87 Atm

**Vo = 2.558 m^3

Table 2

Core Pressure-Volume Relationship
for the 661 MJ CDA

Pressure (MPa)*	Volume (V/Vo)**
27.3	1.00
20.3	1.023
14.73	1.125
10.38	1.405
8.609	1.685
7.077	2.117
5.760	2.826
4.647	3.948
3.708	5.765
2.925	8.604
2.280	12.95
1.755	19.37
1.332	29.47
0.996	45.06

*1 MPa = 10 bars = 9.87 Atm.

**Vo = 2.558 m^3

Table 3

Core Pressure-Volume Relationship
for the 1200 MJ CDA

Pressure (MPa)*	Volume (V/Vo)**
30.0	1.00
20.0	2.25
17.8	2.62
15.0	3.05
12.5	3.65
10.0	4.70
7.5	6.60
6.0	8.40
5.0	10.8
4.0	14.5
3.0	20.2
2.5	25.5
2.0	33.
1.5	50.
1.0	76.
0.7	100.
0.4	140.

*1 MPa = 10 bars = 9.87 Atm

** Vo = 2.558 m^3

Table 4

REXCO Results - Slug Impact Loading on Head

		300MJ CDA	time (msec)	661MJ CDA	time (msec)	1200MJ CDA	time (msec)
Time of Slug Impact	(msec)	114		73		49	
Slug Kinetic Energy	(MJ)	49	114	75	73	142	49
Slug Velocity	(m/sec)	13	113	17	72	27	49
Duration, initial Load Spike	(msec)	2.0		2.0		2.3	
Peak Force, Initial Load Spike	(MN)*	500	115	865	74	1230	50
Head Velocity due to Initial Spike	(m/sec)	0.82		1.4		2.0	
Duration, Slug Loading	(m/sec)	40		55		45	
Peak Force, Slug Loading	(MN)	210	122	280	82	435	59
Equivalent Pressure	(MPa)**	7.0	122	9.4	82	14.6	59
Max. Short-term Averaged Force	(MN)	150		225		285	
Equivalent Pressure	(MPa)	5.0		7.6		9.5	
Average Force, Slug Loading	(MN)	135		180		225	
Equivalent Pressure	(MPa)	4.5		5.9		7.5	

*1MN = 0.2248 Mlbs.

**1MPa = 10 bars = 9.87 Atm. = 145 psi

Table 5

REXCO Results - Selected Pressures and Loads

		300 MJ CDA	time (msec)	661 MJ CDA	time (msec)	1200 MJ CDA	time (msec)
Core Pressure at Problem Start	(MPa)*	7.6	0	27.3	0	30.0	0
Core Pressure at Slug Impact	(MPa)	1.3	114	3.1	73	4.6	49
Core Pressure at Problem End	(MPa	1.9	160	2.3	160	3.1	135
Minimum Core Pressure	(MPa)	1.2	128	2.2	126	3.1	135
Maximum Pressure at Inlet Nozzle							
-before Slug Impact	(MPa)	1.4	28	2.7	35	4.2	37
-after Slug Impact	(MPa)	1.2		4.2		4.6	
Maximum Pressure at Outlet Nozzle							
-before Slug Impact	(MPa)	1.0	8	2.5	11	4.7	19
-after Slug Impact	(MPa)	4.0		4.8		6.2	
Peak Force, Top of CSS Plate	(MN)**	53	48	100	34	180	26
Load on Top of CSS Cone							
-Peak Force before Slug Impact	(MN)	36	74	65	9	135	18
-Max. Short-term Averaged Force after Slug Impact	(MN)	71		140		155	

*1 MPa = 10 bars = 9.87 Atm = 145 psi

**1 MN = 0.2248 Mlbs

Table 6

REXCO Results - Vessel Strains

		300 MJ CDA	time (msec)	661 MJ CDA	time (msec)	1200 MJ CDA	time (msec)
Maximum Core Barrel Strain	(cm/cm)	.004	117	.03	76	.14	132
Maximum Mid Reactor Vessel Strain							
-before Slug Impact	(cm/cm)	.004	41	.01	73	.04	27
-after Slug Impact	(cm/cm)	.04	135	.03	160	.05	135
Maximum Upper Reactor Vessel Strain							
-before Slug Impact	(cm/cm)	.003	87	.002	73	.001	47
-after Slug Impact	(cm/cm)	(.07)*	160	(.09)*	104	(.09)*	92

*After 0.065 strain, the reactor vessel contacts the guard vessel, which is not modeled in REXCO.

Table 7

REXCO Results - Energy Partition

		300 MJ CDA	time (msec)	661 MJ CDA	time (msec)	1200 MJ CDA	time (msec)
Upward Kinetic Energy (KE) at Slug Impact	(MJ)	49	114	75	73	143	49
Upward KE at Problem End	(MJ)	11	160	11	160	22	135
Total KE at Slug Impact	(MJ)	49	114	75	73	143	49
Total KE at Problem End	(MJ)	11	160	13	160	26	135
Maximum Radial KE before Slug Impact	(MJ)	0.9	30	3.2	11	31	17
Radial KE at Slug Impact	(MJ)	0.7	114	1.4	73	2.4	49
Maximum Radial KE after Slug Impact	(MJ)	3.9	117	8.9	75	21	51
Radial KE at Problem End	(MJ)	0.7	160	0.4	160	1.0	135
Core Barrel Strain Energy (SE) at Slug Impact	(MJ)	0.5	114	10	73	67	49
Core Barrel Strain Energy (SE) at Problem End	(MJ)	0.5	160	11	160	67	135
Vessel Wall SE* at Slug Impact	(MJ)	11	114	9.2	73	33	49
Maximum Head Energy at Slug Impact	(MJ)	5.7	160	6.5	123	39	135
Head Energy at Problem End	(MJ)	5.7	160	0.1	160	39	135
Coolant Internal Energy (IE) at Problem Start	(MJ)	0	0	0	0	0	0
Coolant IE at Slug Impact	(MJ)	3.2	114	2.6	73	6.2	49
Coolant IE just after Slug Impact	(MJ)	5.4	116	6.8	74	13.6	50
Coolant IE at Problem End	(MJ)	8.1	160	12.9	160	37.3	135
Core IE at Problem Start	(MJ)	300	0	661	0	1200	0
Core IE at Slug Impact	(MJ)	264	114	567	73	929	49
Core IE at Problem End	(MJ)	258	160	516	160	805	135

Table 7 Cont'd

		300 MJ CDA	time (msec)	661 MJ CDA	time (msec)	1200 MJ CDA	time (msec)
Total Work Energy** at Slug Impact	(MJ)	36	114	94	73	271	49
Total Work Energy at Problem End	(MJ)	42	160	145	160	395	135

*A modeling problem caused errors in the calculation of the reactor vessel wall strain energy after slug impact.
**Total Work Energy = Initial Core Energy - Current Core Energy

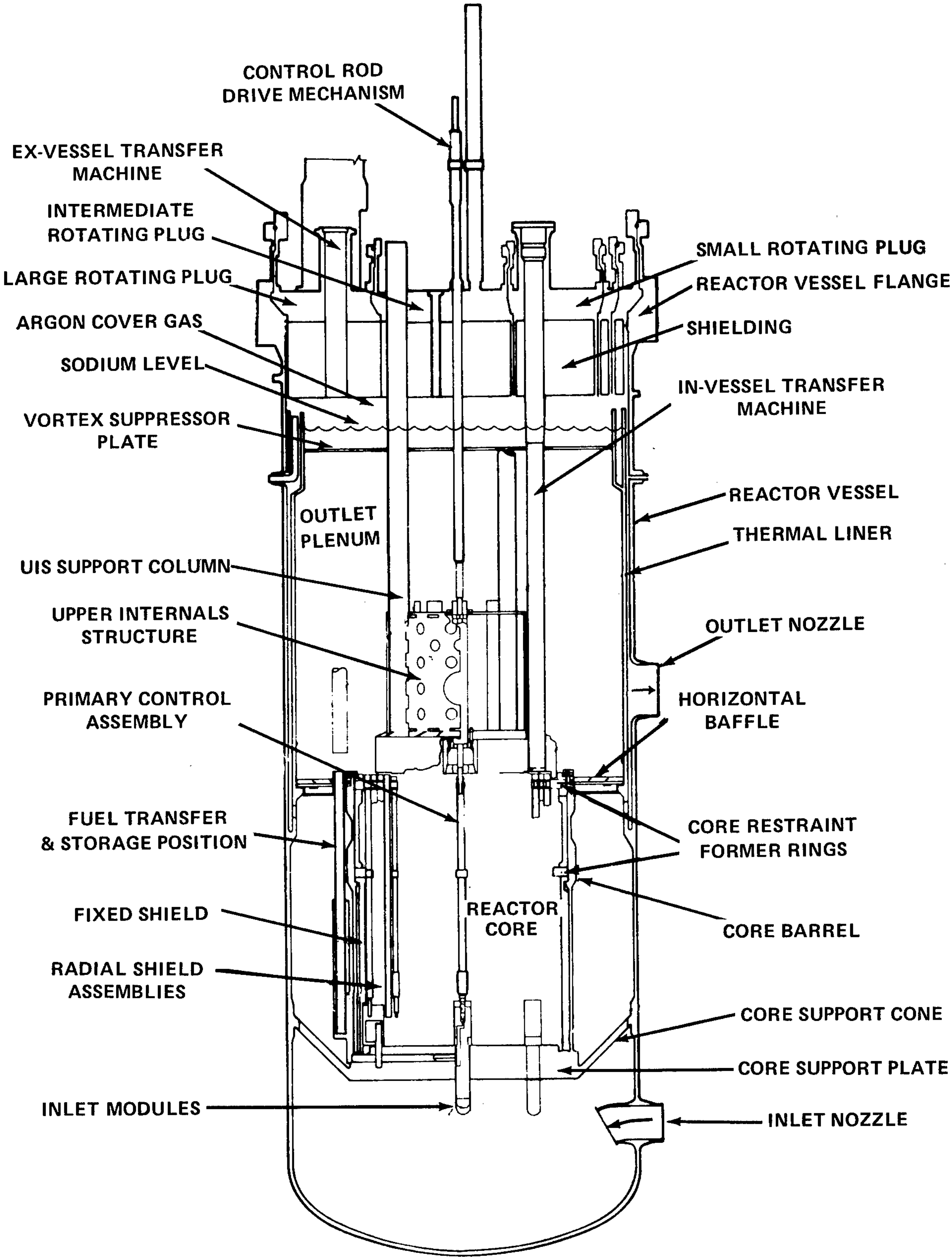
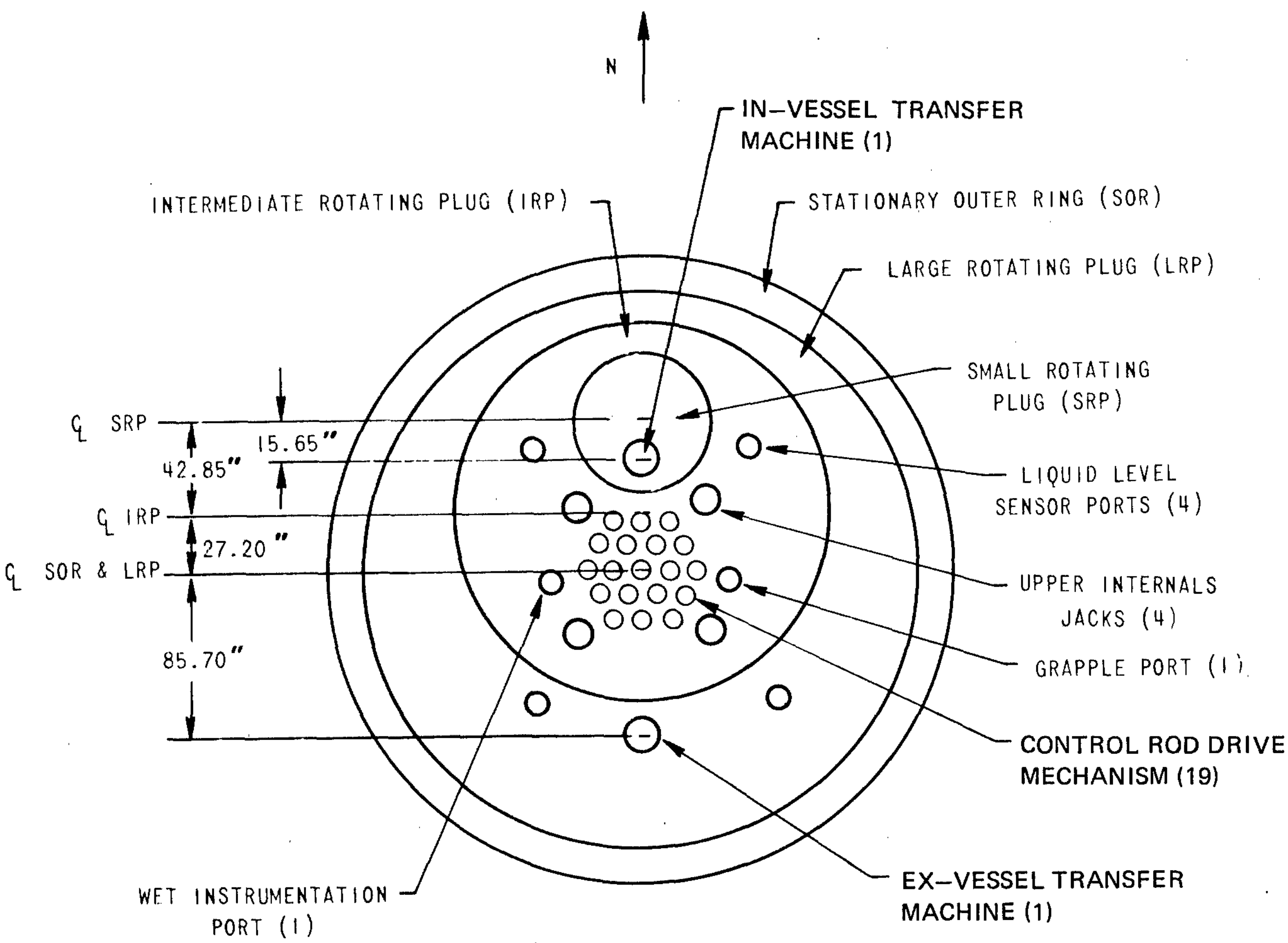


FIG. 1 CRBR REACTOR SCHEMATIC
(FROM FIG. 4.2-36 IN CRBR PSAR)



PLUGS SHOWN IN 0° POSITION (Positive Clockwise)

MOTION RANGE: LRP 0 to ± 180°

IRP 0 to - 180°

SRP 0 to = 180°

FIG. 2 SCHEMATIC-ROTATING PLUGS
(FROM FIG. 2-34 IN CRBR REFERENCE DESIGN REPORT)

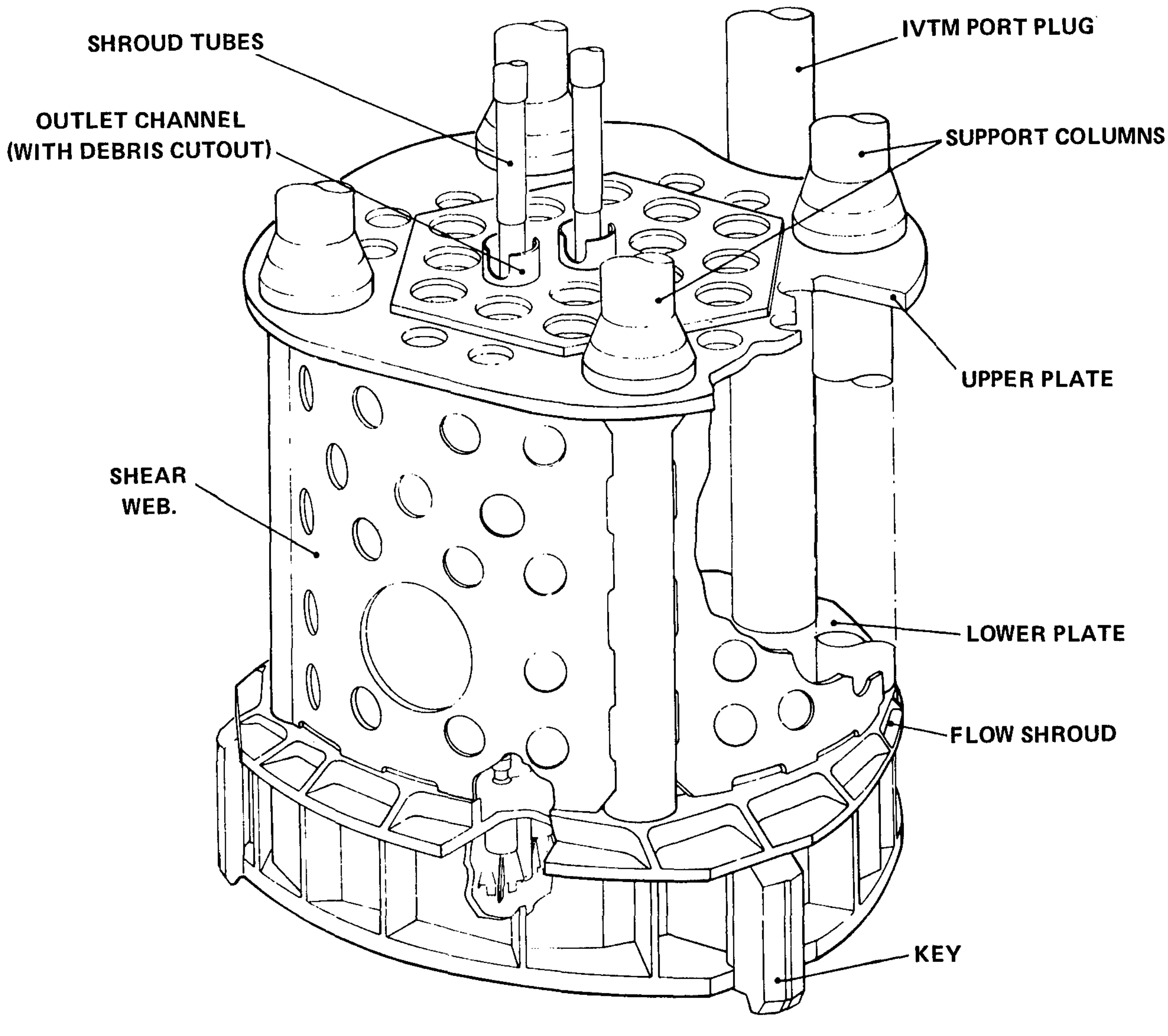


FIG. 3 UPPER INTERNALS STRUCTURE
(FROM FIG. F 7.1-17B IN CRBR PSAR)

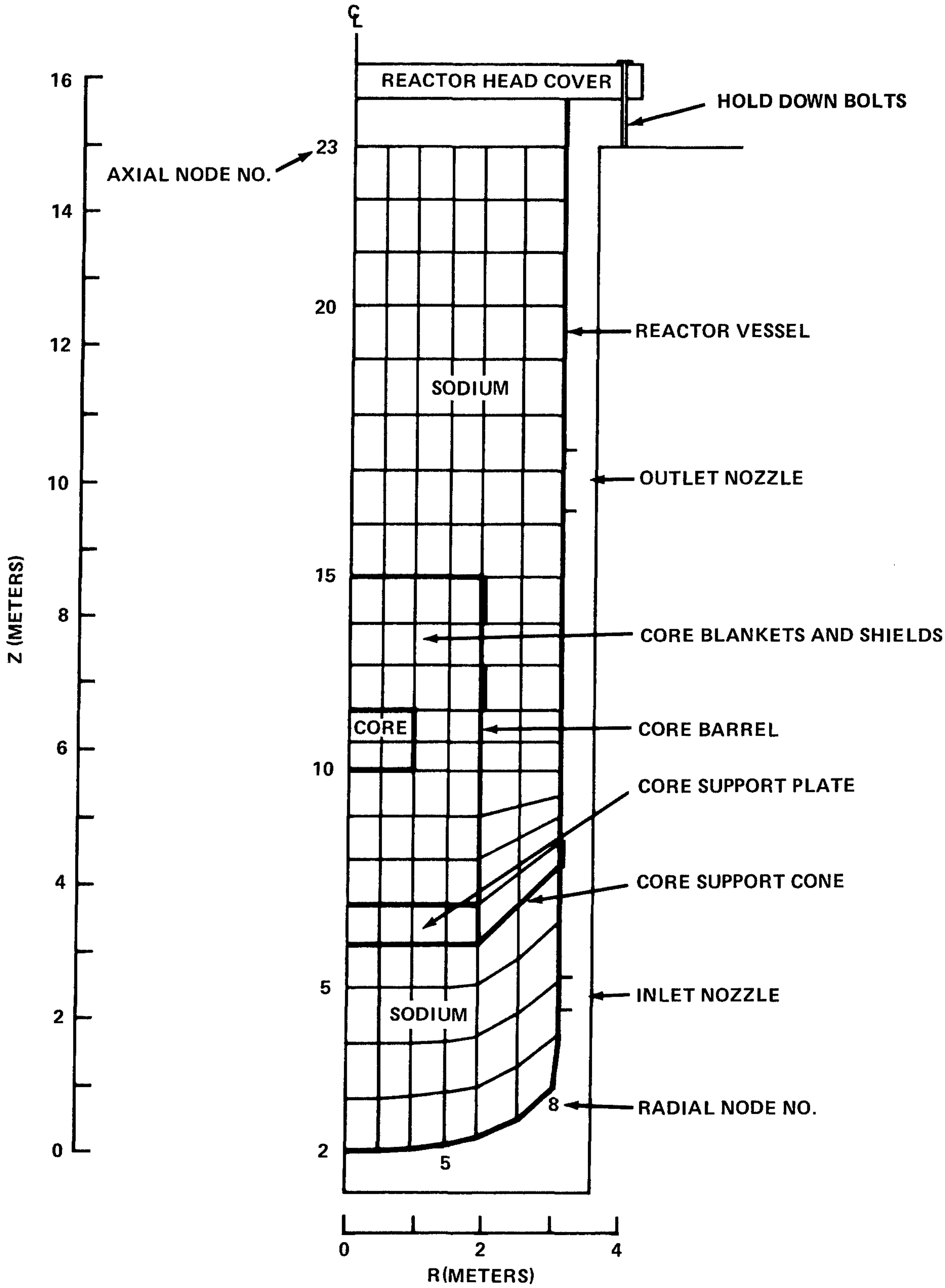


FIG. 4 REXCO–HEP COMPUTER MODEL, NSWC/WOL VERSION

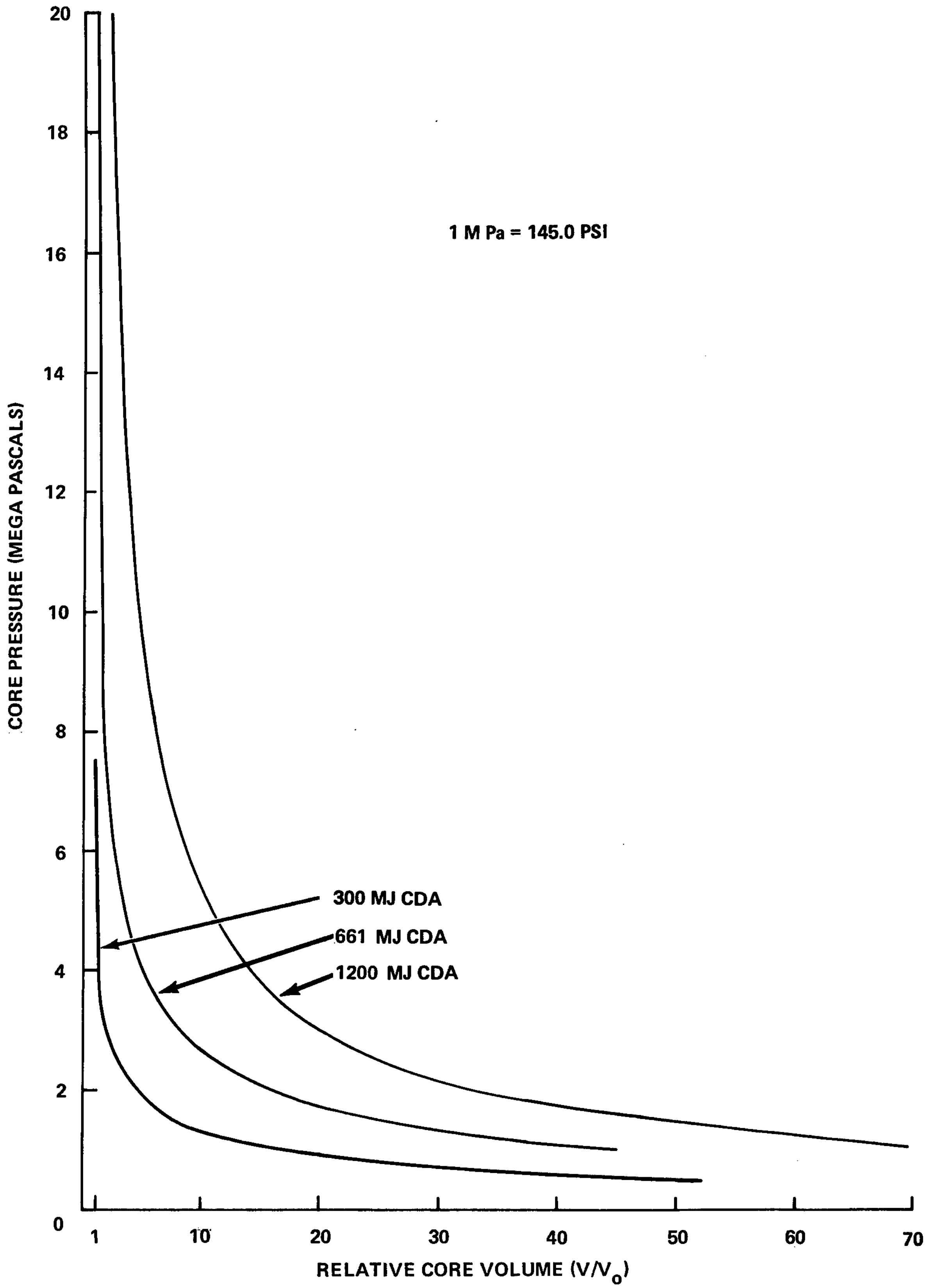


FIG. 5 REXCO INPUT. CORE P–V EXPANSION CURVES

Appendix A

Analysis of the CRBR LRP Shear Ring Response to CDA Loads

Structural Analysis
by
A. S. Kushner
Explosion Dynamics Branch

Hydrodynamic Analysis
by
R. A. Lorenz
Explosion Dynamics Branch

SUMMARY AND CONCLUSIONS

NSWC/WOL is currently evaluating the capability of the CRBR head design to withstand CDAs with energetics of up to 1200 MJ. Three CDAs are being considered, having core mechanical work energy releases of 300 MJ, 661 MJ, and 1200 MJ when expanded to one atmosphere.

The critical component in the CRBR head design is the large rotating plug (LRP) shear ring. Our analyses of the current shear ring designs show that the LRP shear ring is capable of withstanding the 300 MJ CDA, but will fail under the 661 MJ and 1200 MJ loadings.

NSWC/WOL has developed a hold-down concept for the rotating plugs which could replace the shear ring design and which may enable the head to accommodate the 1200 MJ loading. The containment ring in the NSWC/WOL concept remains elastic under the 1200 MJ loading through a point in time at which the entire head is moving downward.

INTRODUCTION

The CRBR reactor head consists of three rotating plugs which transmit CDA loads to each other and to the reactor vessel flange by means of segmented shear rings. It is required that the head remain intact under CDA loads in order that the rotating plugs do not become missiles which can threaten containment integrity.

The object of our task is to evaluate the capability of the Westinghouse Advanced Reactors Division (W-ARD) head design to withstand CDAs with energetics of up to 1200 MJ. The critical components in this design are the shear rings. In the event that our analysis indicates failure of the shear rings within this range of energetics, we have been asked to determine the failure threshold of the W-ARD design and to suggest modifications which would enable the head to accommodate 1200 MJ loads.

Our analysis has proceeded as follows: The NRC staff provided us with pressure vs. volume (P-V) fuel vapor expansion curves for a 300 MJ CDA and for a 1200 MJ CDA. The P-V fuel vapor expansion curve for a 661 MJ CDA is given in Appendix F of the CRBR PSAR. Each of these P-V curves was used as a source term in a hydrodynamic calculation to generate the force-time loading on the reactor head. These force-time loadings were then used as forcing

functions in a structural analysis of the shear rings. Details of the hydrodynamic and structural analyses follow.

HYDRODYNAMIC ANALYSIS

The REXCO-HEP, Release 1, computer code was used to perform the hydrodynamic calculations. REXCO-HEP is a two-dimensional axially-symmetric Lagrangian hydrocode which can incorporate the effects of thin shells, thin plates, and extended structural regions in its calculations.

A schematic of the CRBR is shown in Figure A-1. The REXCO-HEP computer model of the CRBR used in the calculations was developed by NSWC/WOL and is shown in Figure A-2. The reactor vessel and core barrel have been modeled as thin membrane shells while the core support cone has been modeled as a thin membrane plate. The core support plate is modeled as an extended structural region. The reactor head in a REXCO calculation can be modeled only as a rigid, monolithic, circular plate. The mass of the head includes the mass of the shielding and components attached to it. The upper internals structure (UIS) is not included in the REXCO model since there is no way at present to model the effects of the UIS support columns. Upper bound sodium slug impact loads on the head are generated when the UIS is ignored, although the true loading time history on the head is distorted. W-ARD analysis indicates that maximum stresses are calculated for the shear rings when preloading of the shear rings through the UIS support columns is eliminated. Based on these considerations, we are calculating the maximum damage to the head by ignoring the effects of the UIS.

The P-V fuel vapor expansion curves used as source terms in the hydrodynamic calculations are shown in Figure A-3. The 300 MJ curve and the 1200 MJ curve were provided by the NRC staff while the 661 MJ curve was specified in Appendix F of the CRBR PSAR. Each P-V curve represents the equation of state used for the four zones marked "CORE" in Figure A-2.

In the hydrodynamic calculation, the unbalanced pressure in the core region seeks relief by distorting and moving the surrounding material. Axially, the expanding core accelerates the sodium slug upward until the slug hits the reactor head. The head then moves freely upward for a short distance, resisted only by gravity, to simulate the motion allowed by the 1/4 inch (0.635 cm) gaps between the three rotating plugs and their shear rings.

The resulting force-time loading histories on the head for the 300, 661, and 1200 MJ CDAs are given, respectively, in Figures A-4, A-5, and A-6. These loading histories are used as input to the structural analysis calculations as described below.

STRUCTURAL ANALYSIS

The head loading curves (Figures A-4, A-5, and A-6) generated by REXCO are separated into an impulsive phase and a transient loading phase for the structural analysis. The impulsive phase consists of the initial spike of the force versus time curve and is assumed to impart an initial vertical rigid body velocity to the head and the head mounted components. The remainder of the REXCO load is applied as a time dependent load acting on the lower surface of the head. The impulsive velocities imparted are 31.5 in/sec (80cm/sec) for the 300 MJ CDA, 55 in/sec (140 cm/sec) for the 661 MJ CDA, and 80 in/sec (203 cm/sec) for the 1200 MJ CDA. The transient forces used as structural loading are shown in Figures A-7, A-8, and A-9. These curves are smoothed representations of Figures A-4, A-5, and A-6.

The structural analysis of the shear ring-head system is a three-dimensional problem. The head consists of three eccentrically situated circular plugs as shown in Figure A-10. The shear rings are made as a series of circular arc sectors which are not connected in the circumferential direction. Because a three-dimensional, dynamic, elastic-plastic analysis is beyond the computational capabilities currently existing at NSWC/WOL, the problem was simplified while still maintaining a worst-damage representation of the structural response of the large rotating plug (LRP) shear ring. The NONSAP code in use at NSWC/WOL is capable of performing two-dimensional plane and axisymmetric, dynamic, elastic-plastic analyses. Due to the segmented construction of the shear rings, the stress state in the shear rings will be predominently two-dimensional. Ignoring the effects of the small and intermediate rotating plug shear rings on load transfer, and treating the three rotating plugs as one large axisymmetric region should result in a conservative approximation of the load transfer to the LRP shear ring.

Figure A-11 shows the LRP shear ring configuration considered and Figure A-12 shows the mesh used in the NONSAP analysis. The mass of the shielding and head-mounted components was evenly distributed throughout the left-most twelve elements of the LRP shown in Figure A-12. The shear ring and the LRP lip were modeled as bilinear elastic-plastic materials. The reactor vessel flange and the remainder of the LRP were modeled as linear elastic materials. The shear ring was treated as a plane stress region, all other regions were axisymmetric bodies. The material properties used in the calculations are given in Table A-1.

The LRP shear ring was found to be capable of stopping the head under the impulsive load for all three CDA loadings considered. Although there was a substantial region of plastic deformation in the shear ring, this deformation was not severe enough to cause gross structural failure of the shear ring. However, when the total load was applied, the head was found to crush the shear ring and continue upward for the 661 MJ and 1200

MJ cases. For the 300 MJ case, the shear ring was able to stop the head without being completely crushed. Figures A-13, A-14, and A-15 show the critical stress regions in the LRP shear ring during a time sequence just before failure for the 661 MJ loading. The top two values listed in each region are the maximum and minimum principal stresses. The bottom value is the von Mises equivalent stress. Analysis of the stress field indicates that, except for a region of crushing at the LRP lip-shear ring interface, the shear ring is failing in a bending-shear mode.

During the current study, a W-ARD drawing of a proposed design change for the shear ring configuration was received. The major difference in the new design was the elimination of the shear ring support ledge in the reactor vessel flange, shown in Figures A-13, A-14, and A-15. When this change was made in the NONSAP model, no change in the failure level was found. In the new design, the shear ring tends to rotate away from the reactor vessel flange and be crushed in a pure compression mode. Figures A-16, A-17, and A-18 illustrate the stress build-up during this crushing process for the 661 MJ loading.

FAILURE CRITERION

In assessing the structural capabilities of the LRP shear ring for retaining the reactor head under CDA loading conditions, a modified (by NSWC/WOL) ASME code faulted design criterion is used. For inelastic system and component analysis, the ASME code requirement is a limit on the maximum effective stress to a value equal to 0.7 σ_u The effective stress can be that corresponding to either the von Mises or Tresca theories of yield. In our analysis the von Mises stress was used.

In view of the nature in which the shear ring is loaded, a strict adherence to the ASME code seems unnecessarily stringent. When the reactor head impacts the LRP shear ring, a region of local plastic deformation will generally form around the impacting surfaces. Requiring the stresses in this region to remain less than 0.7 σ_u does not represent a meaningful criterion for deciding whether the LRP shear ring is capable of retaining the reactor head. The manner and degree to which the plastic zone may be allowed to spread and the maximum value which the stresses may be allowed to reach in the plastic region are highly dependent on the manner in which the structure would ultimately fail. Hence no strict general requirement can be stated and each design must be assessed individually.

The actual criterion used was to assess the degree to which the plastic zone spread and the manner in which the reactor head was brought to rest. As an example, in the 300 MJ CDA analysis, the plastic zone spread over a region less than 20 percent of the LRP shear ring thickness and had stopped spreading when our computations indicated that the upward motion of the reactor head had terminated. This was considered an acceptable case. How-

ever, for the 661 and 1200 MJ CDAs, the plastic zone spread over the entire shear ring with stresses everywhere exceeding 0.7 σ_u and the reactor head was still moving upward at this time. This obviously represents an unacceptable case. Inherent in this criterion is a requirement that the stress level in the plastic region does not markedly exceed 0.7 σ_u and approach the stress level at which rupture would initiate.

This criterion is based on our experience in the analysis and design of structures made of ductile materials and designed for impact loadings.

FEASIBILITY STUDY OF MEETING THE 1200 MJ CRITERION

The structural analysis of the W-ARD design pinpointed several conceptual weaknesses in their approach to head containment. However, it was not clear that even by improving on these weak points could a workable design capable of meeting the 1200 MJ criteria be evolved. For this reason, a study has been undertaken to evaluate possible improved design concepts. The study of the W-ARD designs indicated three major weaknesses. First, because of its segmented nature, the shear ring is inherently weaker than an identical one-piece axisymmetric structure. Second, because of the narrow radial width of the shear ring, the impact loading of the LRP lip is applied over a small area causing gross crushing of the material in this region. Third, again because of its narrow radial width, the shear ring is not flexible and can not distribute the load absorption over a broad region.

Figure A-11 illustrates the shear ring concept as proposed by W-ARD. As can be seen, although there is a large region of the reactor vessel flange which could be used to absorb the impact energy of the head, the shear ring geometry does not allow for such a transfer of energy in an efficient manner. Figure A-19 illustrates the proposed flexible ring concept. The LRP ring shown is an axisymmetric structure which is to be bolted to the reactor vessel flange. This design offers over 50% more contact area with the LRP lip, and also offers a wider, more flexible geometry capable of deflecting upward with the LRP lip and still absorbing most of the impact energy in an elastic manner. To test the ability of this concept to safely contain the head under the loading generated by a 1200 MJ CDA, the existing NONSAP finite element model of the W-ARD design was modified as shown in Figure A-20. Assuming the hold down ring to be rigidly restrained should provide a worst case analysis of the stresses in the ring. The reactor vessel head was subjected to the loading shown in Figure A-9 plus an initial vertical velocity of 80 in/sec (203 cm/sec) upward. The results of this analysis are very encouraging. Figure A-21 is a plot of the vertical velocity of the center of the reactor head versus time. At approximately 17 mseconds the entire head is moving downward and can be assummed to have separated from the

hold down ring. During the period up to 17 mseconds, the most severe stress state in the LRP lip and the hold down ring occurred at 15.5 mseconds and the von Mises stresses for elements in the finite element mesh at this time are shown in Figures A-22 and A-23. As can be seen from Figure A-22, while much of the LRP lip has gone plastic, the stress levels are all very close to the yield point and in none of the elements does the stress level even approach 63,000 psi (435 MPa) which is equal to 0.7 σ_u for the head material. Figure A-23 shows that except for small regions at the contact surface and around the constraints the hold down ring is behaving elastically.

It must be emphasized that this analysis was purely an exercise to assess the feasibility of the concept and does not represent an actual design.

Table A-1

Material Properties used in the
NONSAP Finite Element Analysis

Rotating Plugs and Reactor Vessel Flange

Yield Stress	σ_y = 50,000 psi	(345 MPa)
Ultimate Stress	σ_u = 90,000 psi	(621 MPa)
0.7 Ultimate Stress	$0.7\sigma_u$ = 63,00 psi	(434 MPa)
Elastic Modulus	$E = 30 \times 10^6$ psi	(2.07×10^{11} Pa)
Poisson's Ratio	$\nu = 0.3$	
Tangent Modulus ($d\sigma/d\varepsilon^P$)	E_T = 170,000 psi	(1.17×10^9 Pa)

Shear Ring

Yield Stress	σ_y = 90,000 psi	(621 MPa)
Ultimate Stress	σ_u =150,000 psi	(1030 MPa)
0.7 Ultimate Stress	$0.7\sigma_u$=105,000 psi	(724 MPa)
Elastic Modulus	$E = 30 \times 10^6$ psi	(2.07×10^{11} Pa)
Poisson's Ratio	$\nu = 0.3$	
Tangent Modulus ($d\sigma/d\varepsilon^P$)	E_T=310,000 psi	(2.14×10^9 Pa)

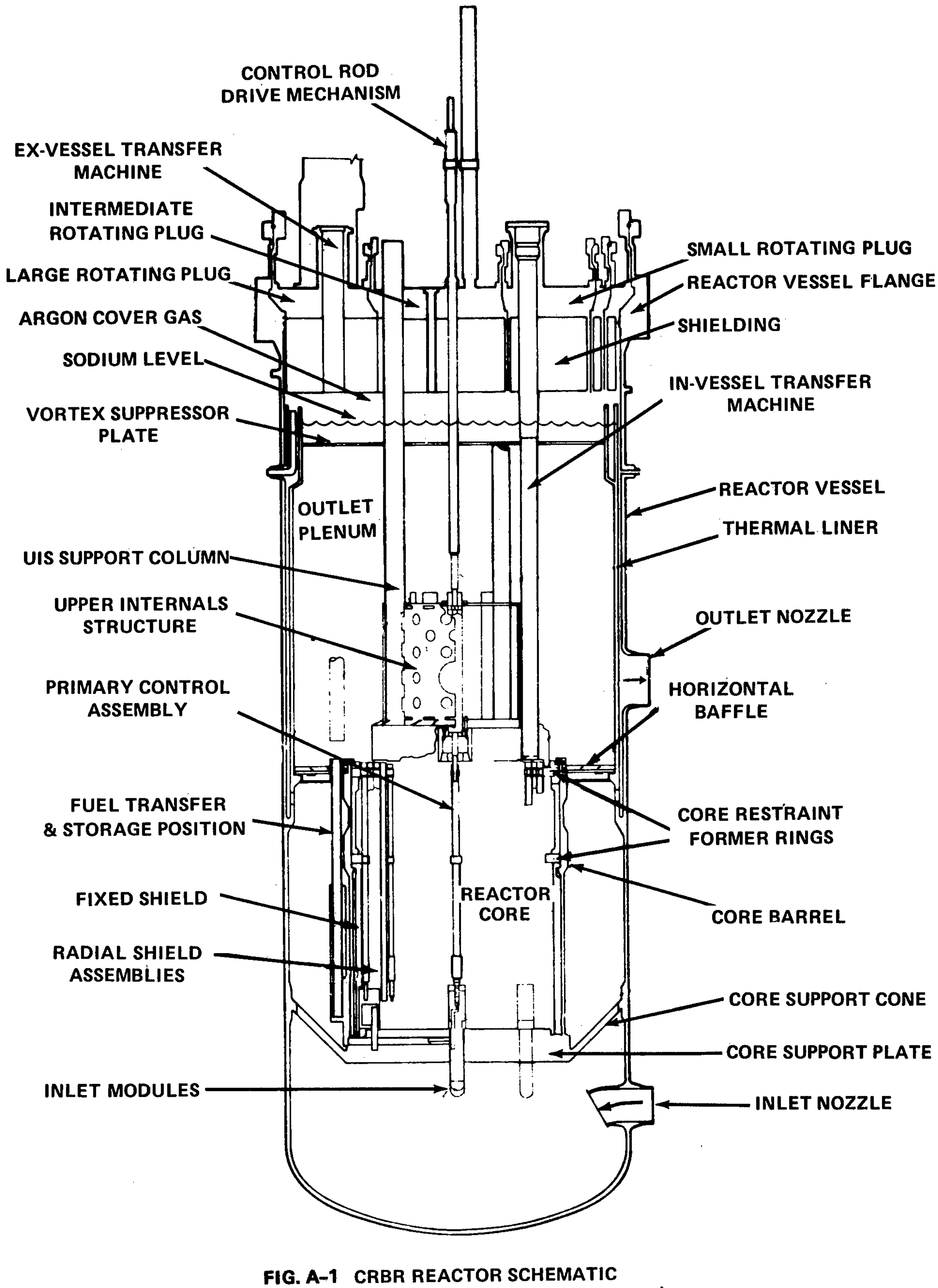


FIG. A-1 CRBR REACTOR SCHEMATIC
(FROM FIG. 4.2 - 36 IN CRBR PSAR)

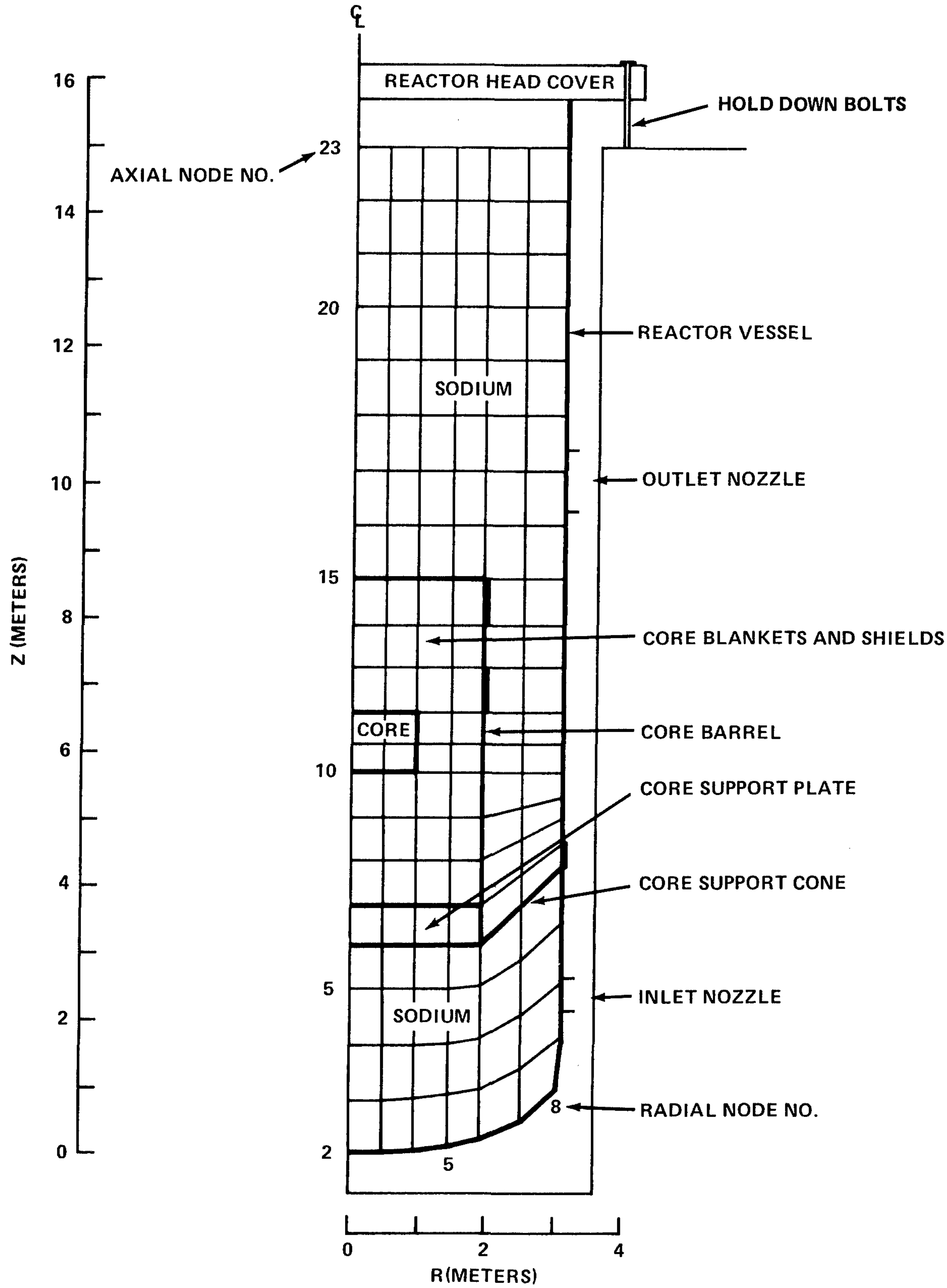


FIG. A-2 REXCO–HEP COMPUTER MODEL, **NSWC/WOL VERSION**

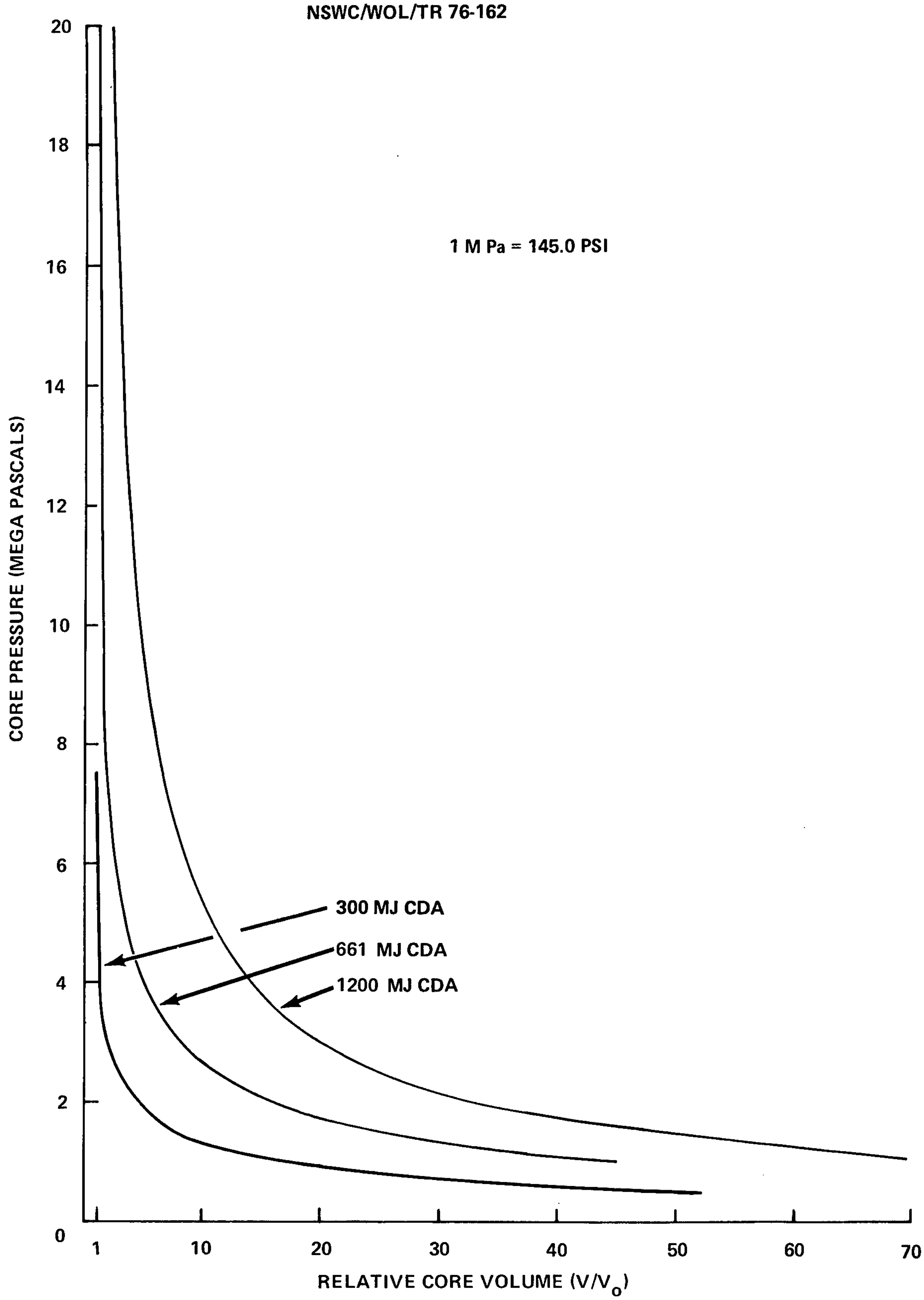


FIG. A-3 REXCO INPUT. CORE P—V EXPANSION CURVES

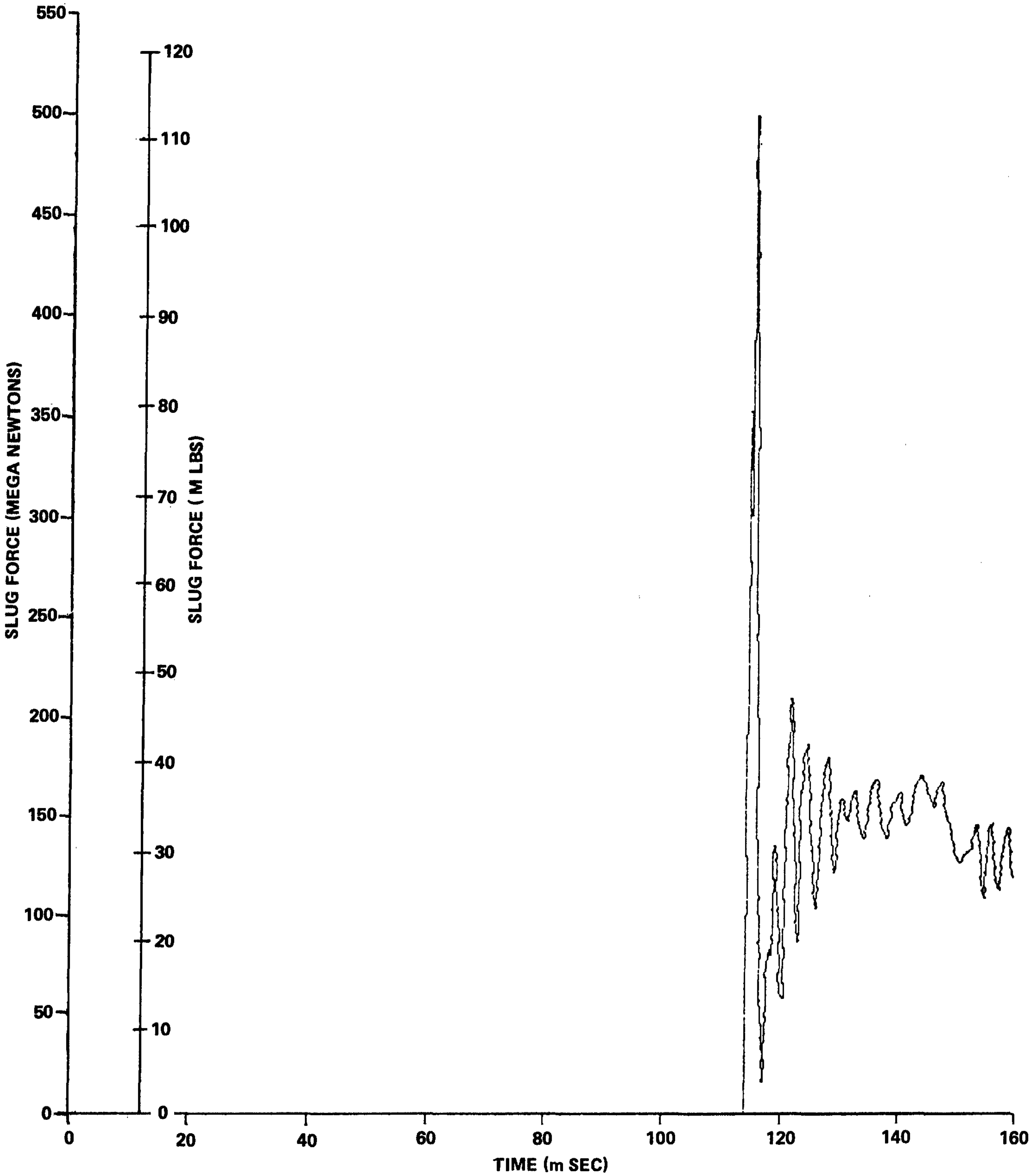


FIG. A-4 REXCO RESULTS FOR THE 300 MJ CDA, SLUG FORCE ON REACTOR HEAD

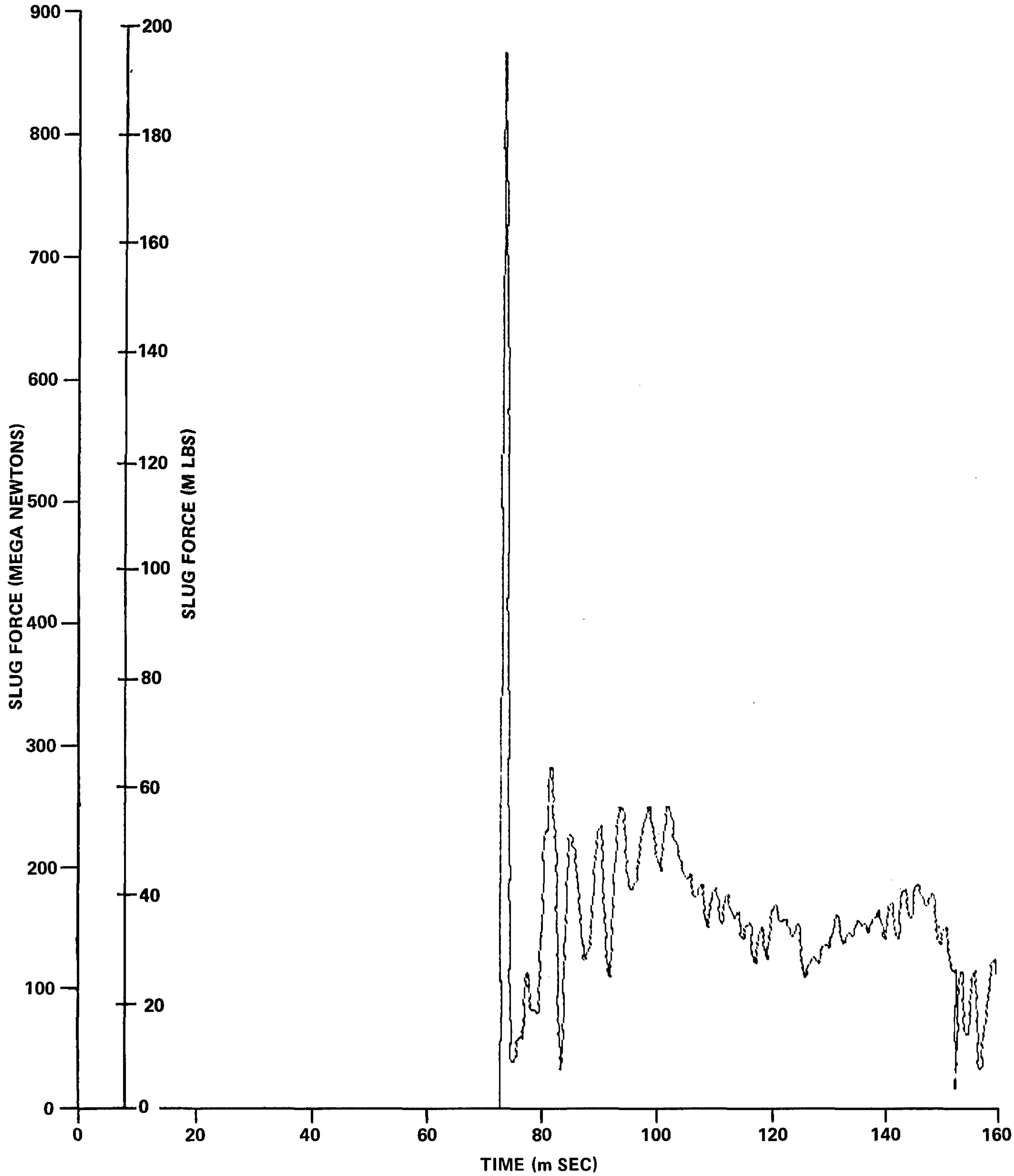


FIG. A-5 REXCO RESULTS FOR THE 661 MJ CDA.
SLUG FORCE ON REACTOR HEAD

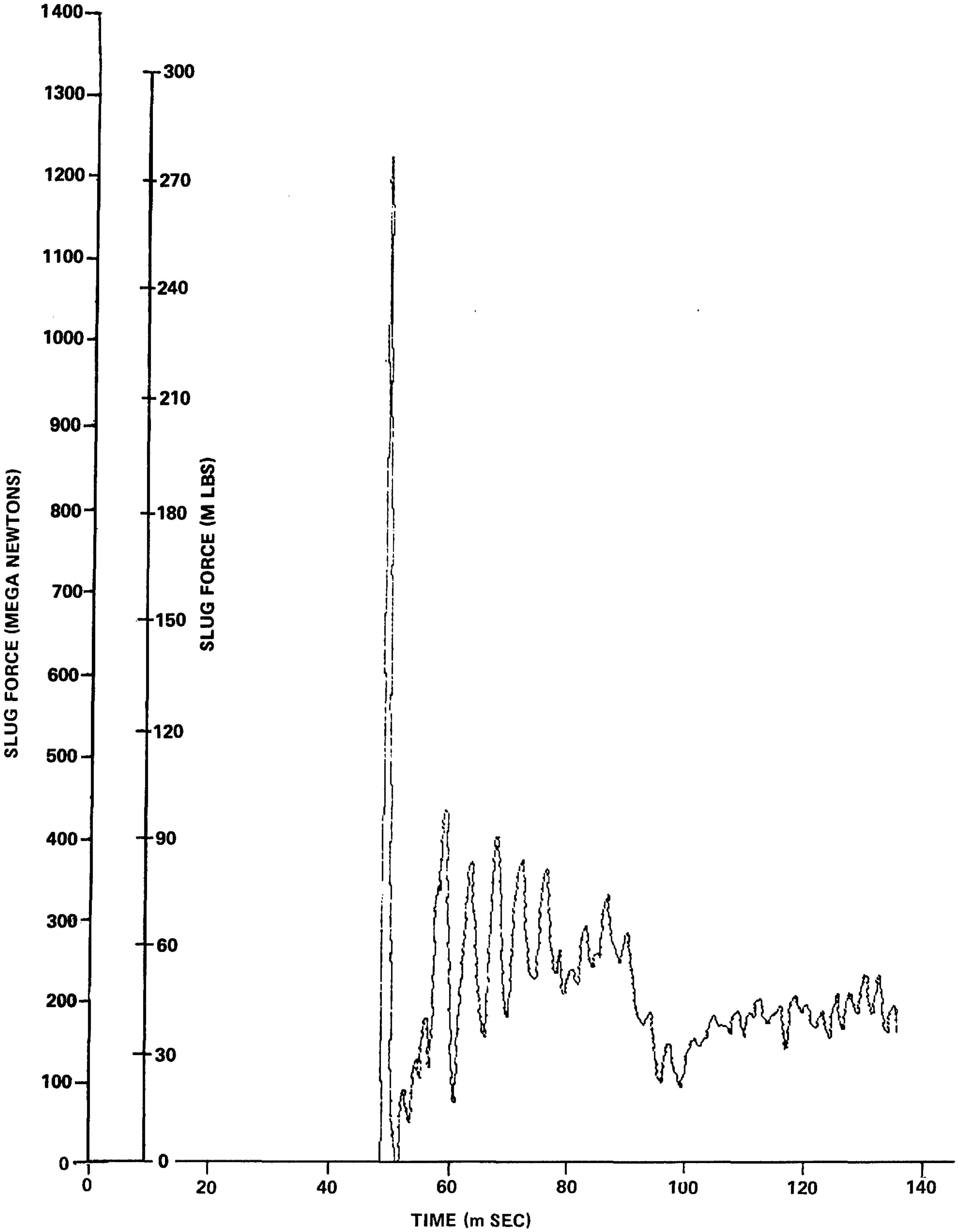


FIG. A-6 REXCO RESULTS FOR THE 1200 MJ CDA.
SLUG FORCE ON REACTOR HEAD

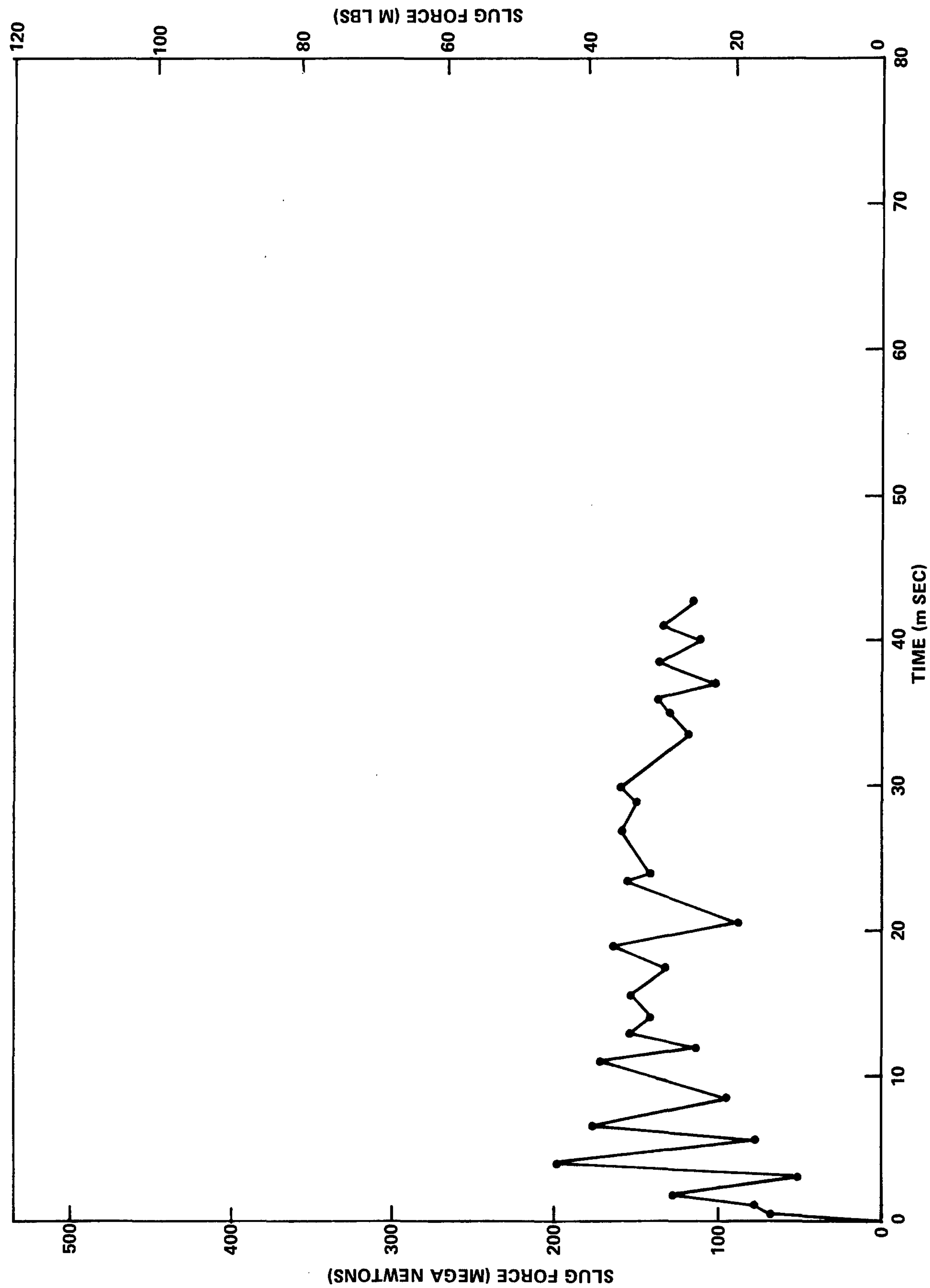


FIG. A-7 NONSAP INPUT FOR THE 300 MJ CDA.
SLUG FORCE ON REACTOR HEAD

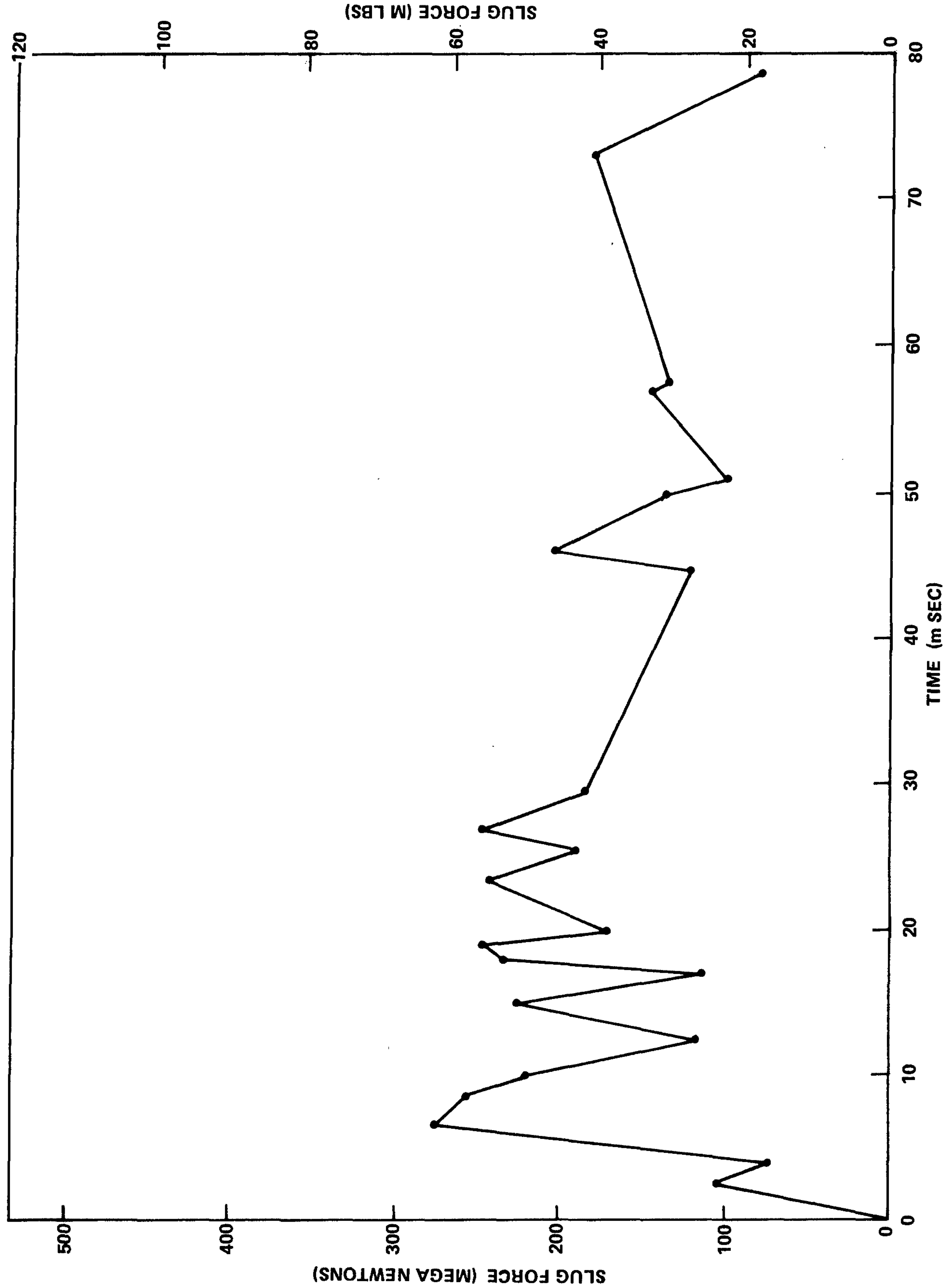


FIG. A-8 NONSAP INPUT FOR THE 661 MJ CDA.
SLUG FORCE ON REACTOR HEAD

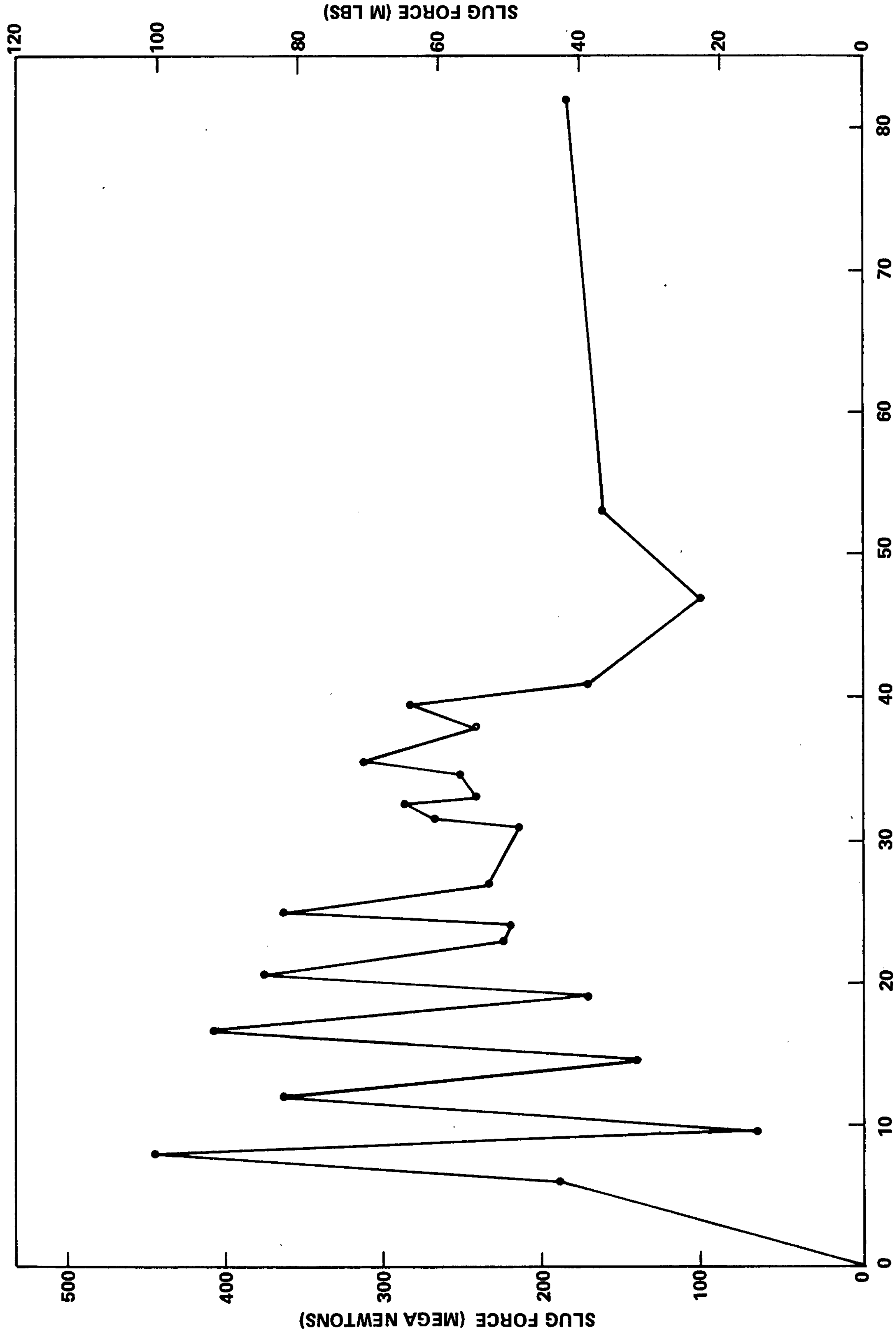
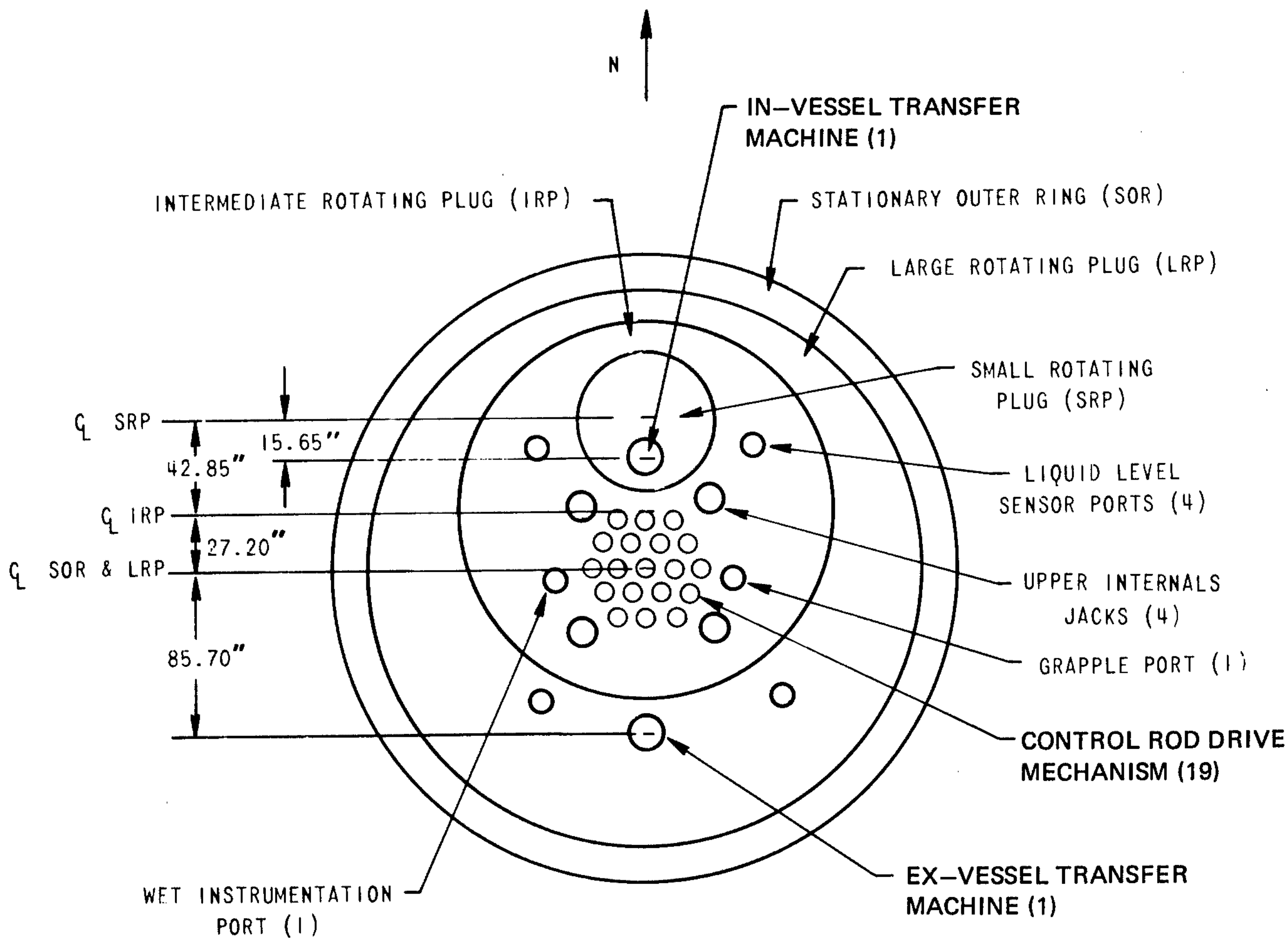


FIG. A–9 NONSAP INPUT FOR THE 1200 MJ CDA, SLUG FORCE ON REACTOR HEAD



PLUGS SHOWN IN 0° POSITION (Positive Clockwise)

MOTION RANGE: LRP 0 to ± 180°

IRP 0 to - 180°

SRP 0 to = 180°

FIG. A-10 SCHEMATIC- ROTATING PLUGS

(FROM FIG. 2-34 IN CRBR REFERENCE DESIGN REPORT)

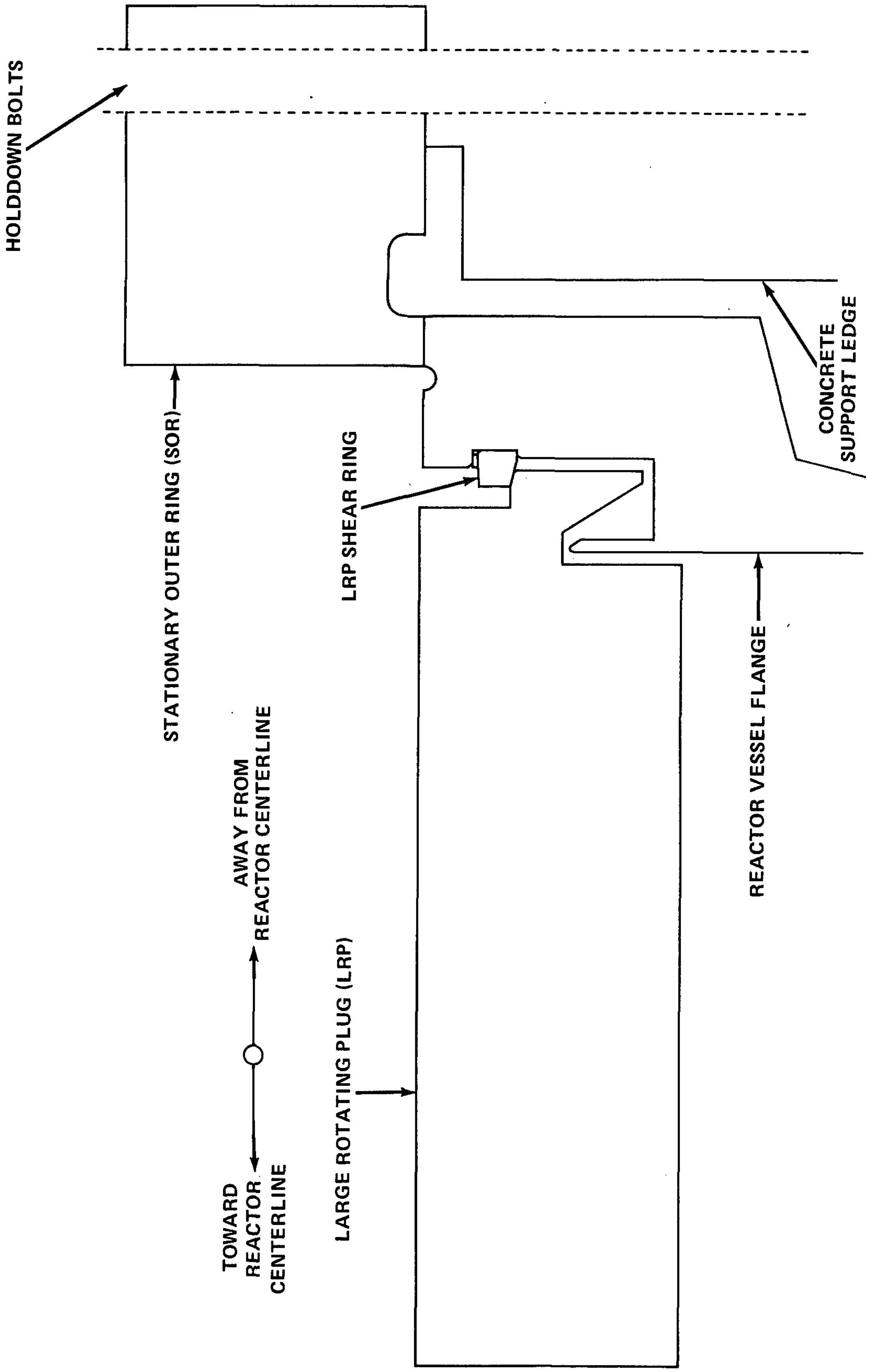


FIG. A-11 LRP SHEAR RING CONFIGURATION

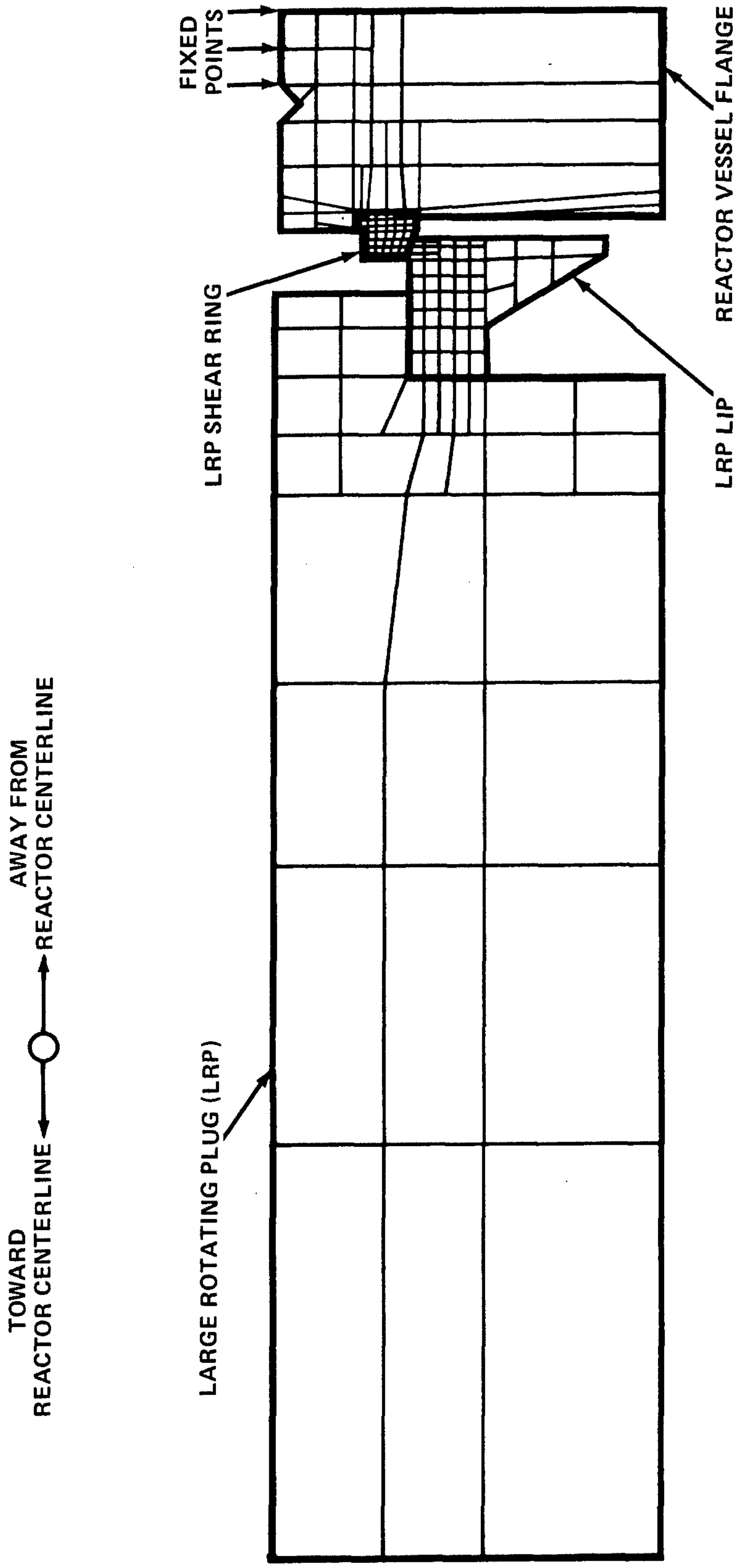


FIG. A-12 NONSAP LRP SHEAR RING COMPUTER MODEL

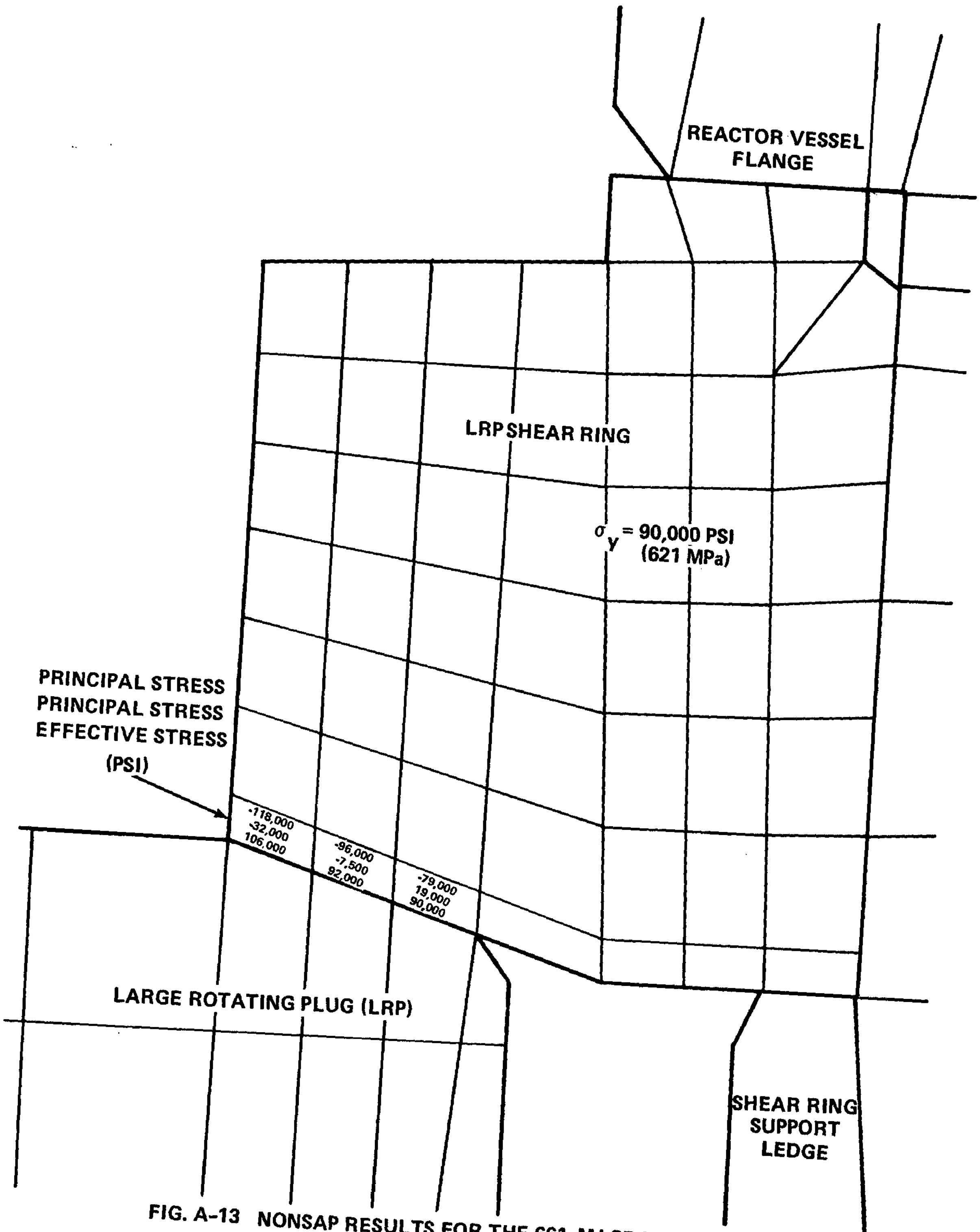


FIG. A-13 NONSAP RESULTS FOR THE 661 MJ CDA
(WITH SHEAR RING SUPPORT LEDGE)
CRITICAL STRESSES AT t = 3.65 m SEC

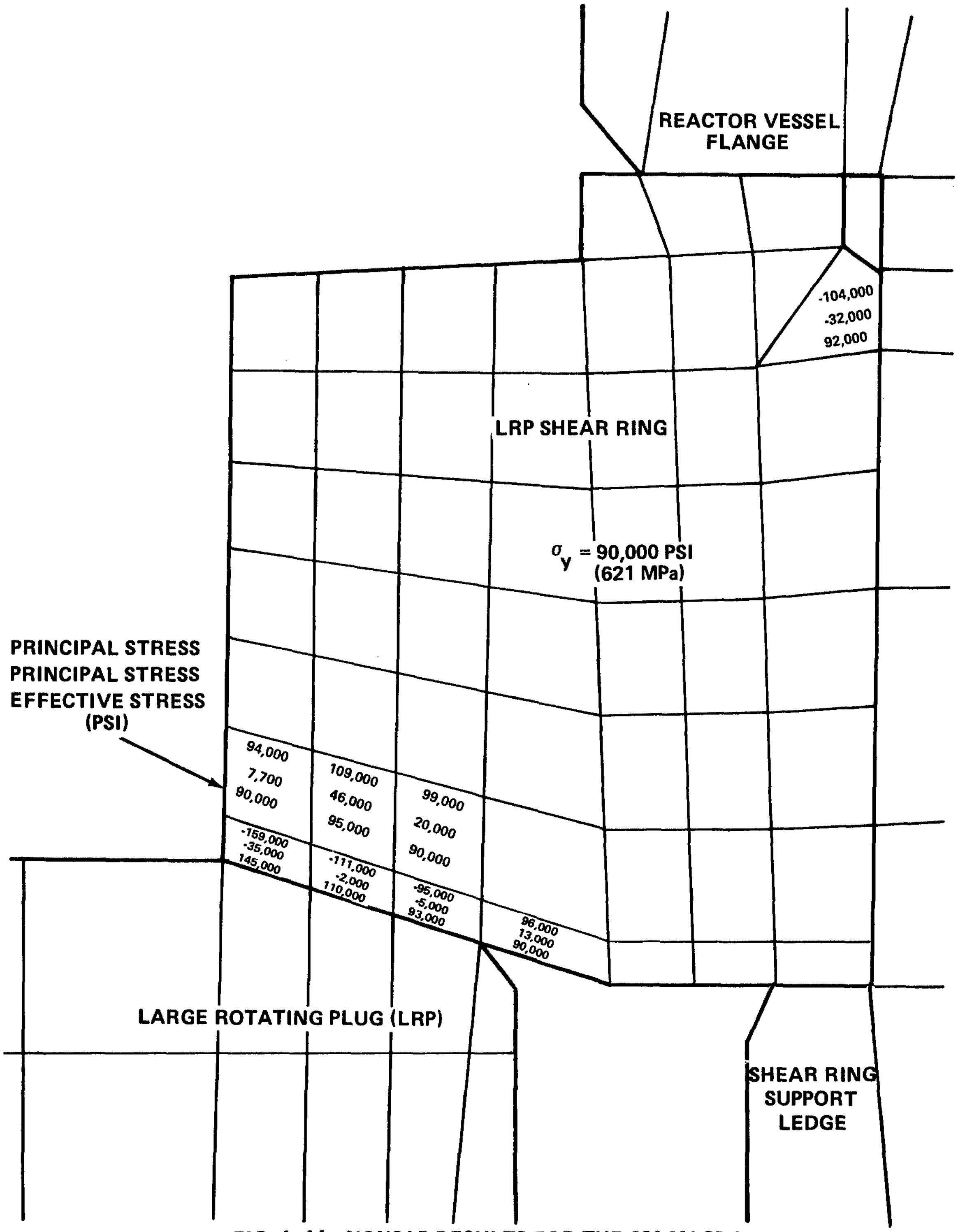


FIG. A-14 NONSAP RESULTS FOR THE 661 MJ CDA
(WITH SHEAR RING SUPPORT LEDGE)
CRITICAL STRESSES AT t = 3.8 m SEC

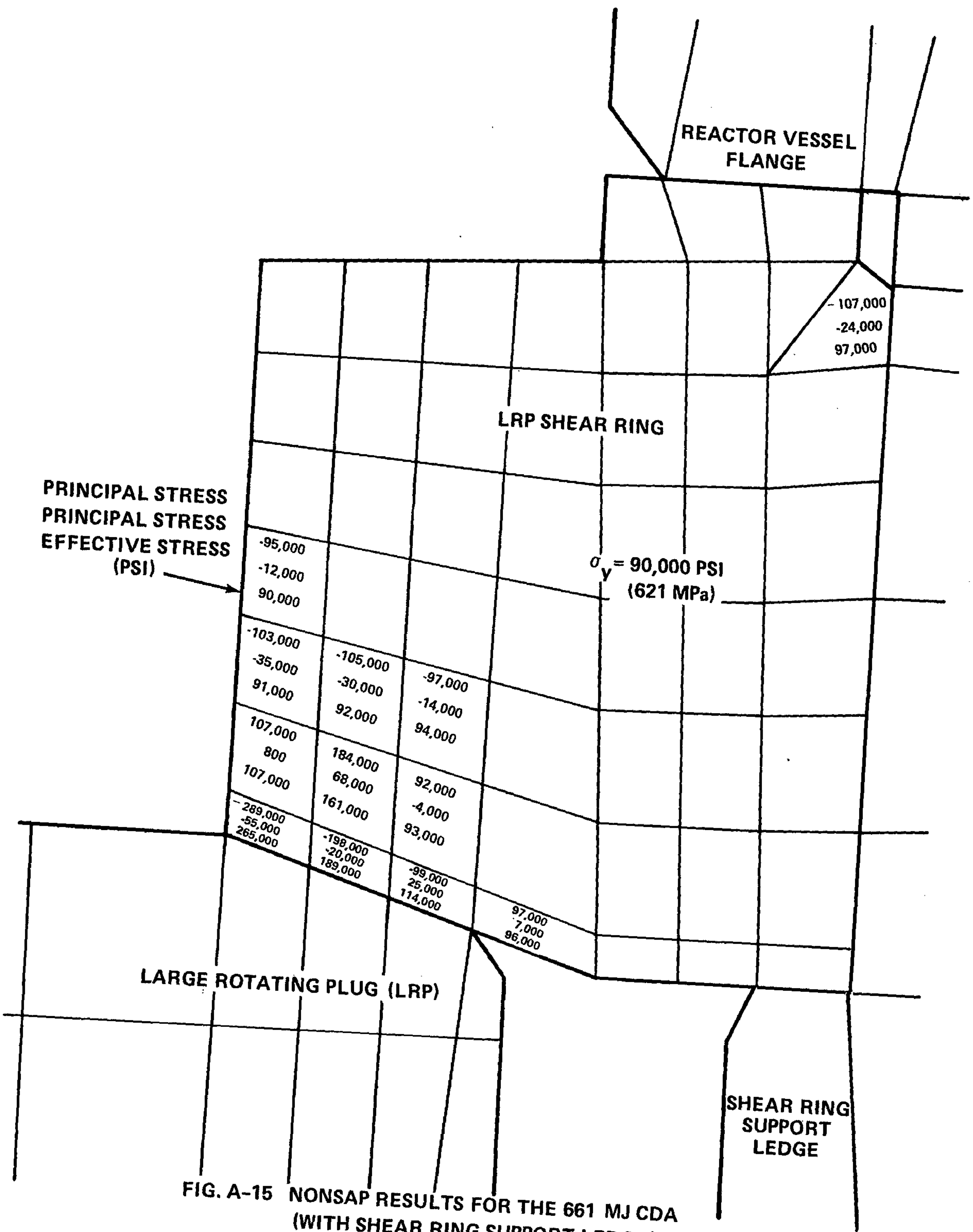


FIG. A-15 NONSAP RESULTS FOR THE 661 MJ CDA
(WITH SHEAR RING SUPPORT LEDGE)
CRITICAL STRESSES AT t = 3.9 m SEC

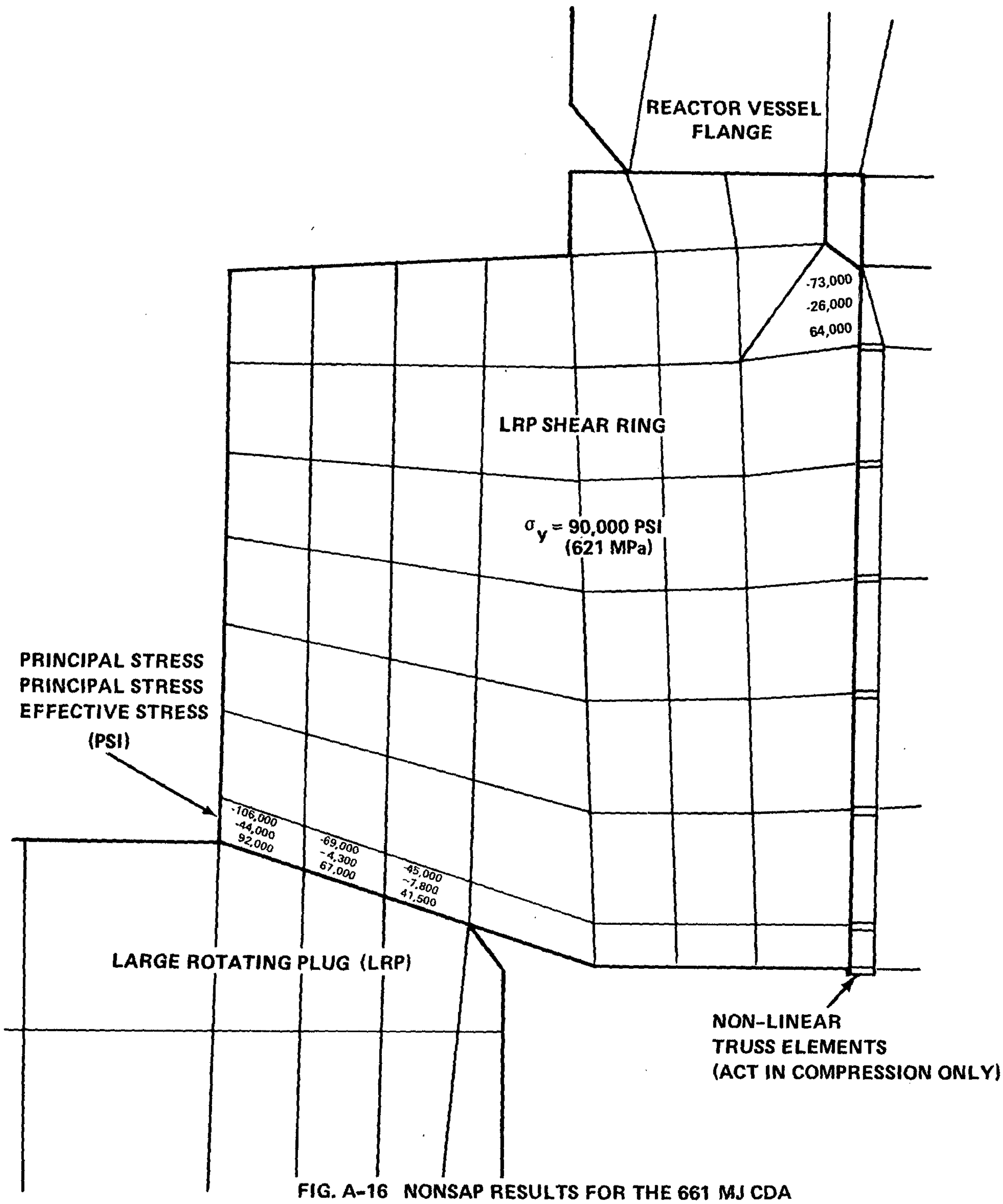


FIG. A-16 NONSAP RESULTS FOR THE 661 MJ CDA
(WITHOUT SHEAR RING SUPPORT LEDGE)
CRITICAL STRESSES AT t = 2.0 m SEC

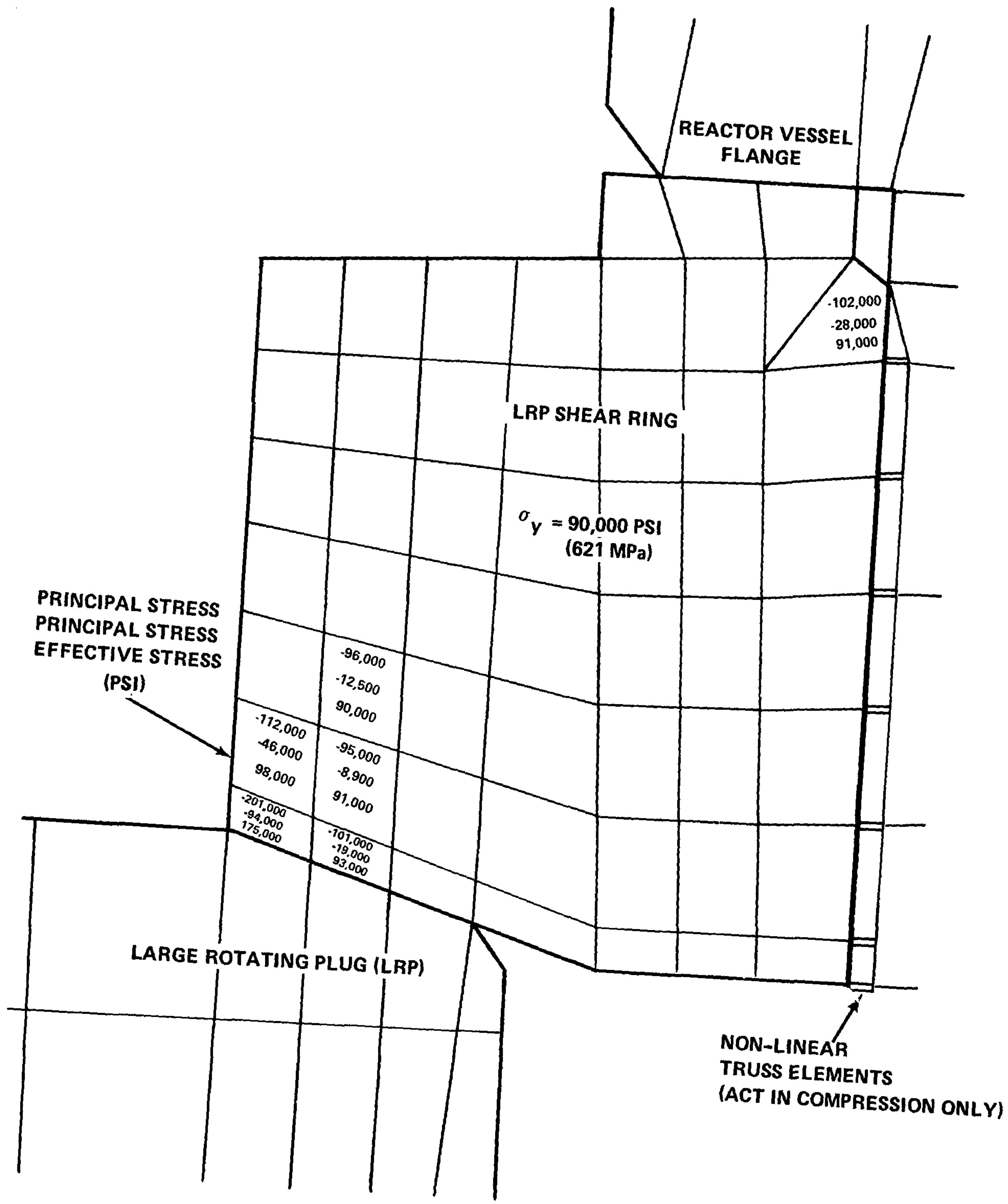


FIG. A-17 NONSAP RESULTS FOR THE 661 MJ CDA
(WITHOUT SHEAR RING SUPPORT LEDGE)
CRITICAL STRESSES AT t = 2.5 m SEC

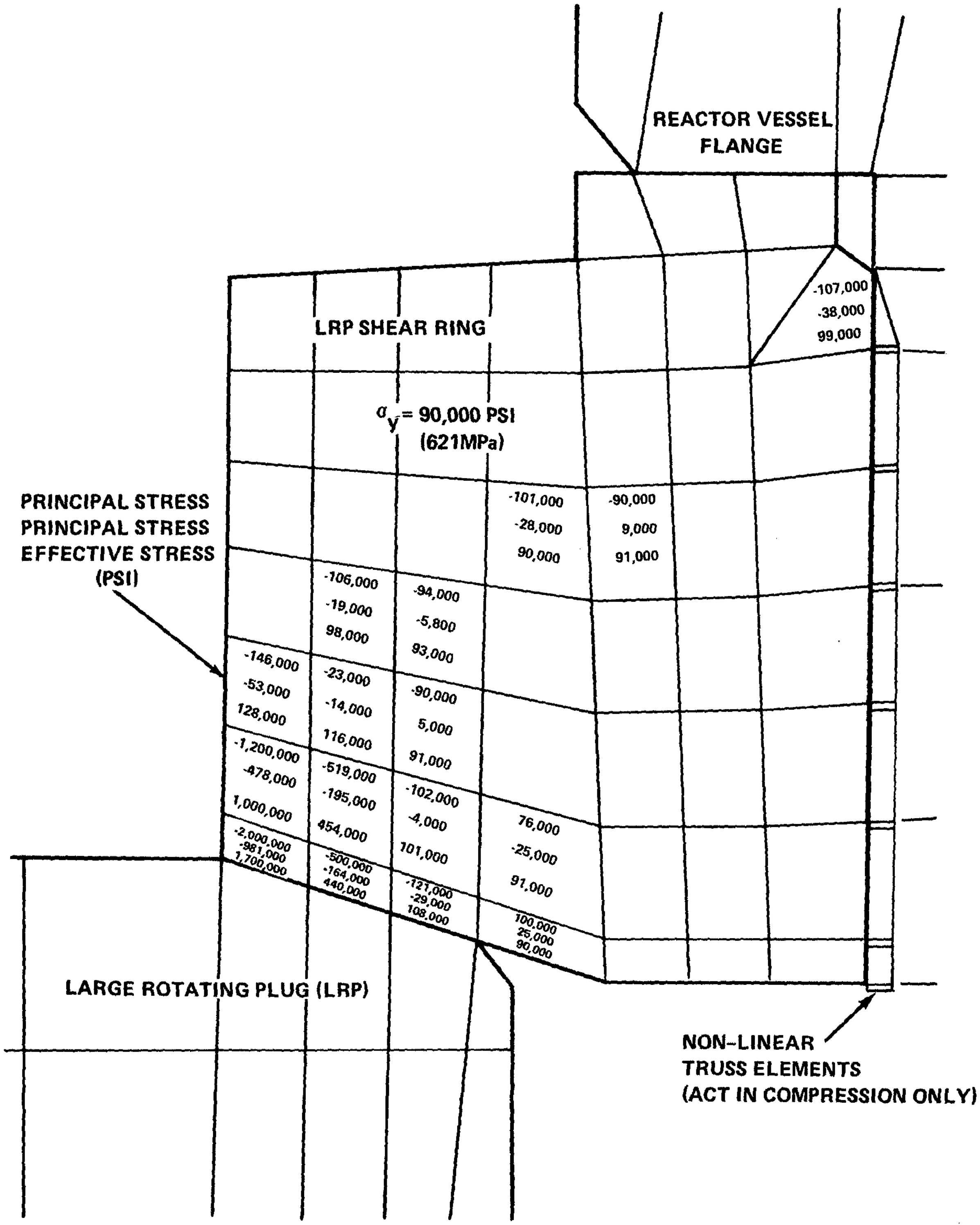


FIG. A-18 NONSAP RESULTS FOR THE 661 MJ CDA
(WITHOUT SHEAR RING SUPPORT LEDGE)
CRITICAL STRESSES AT t = 2.7 m SEC

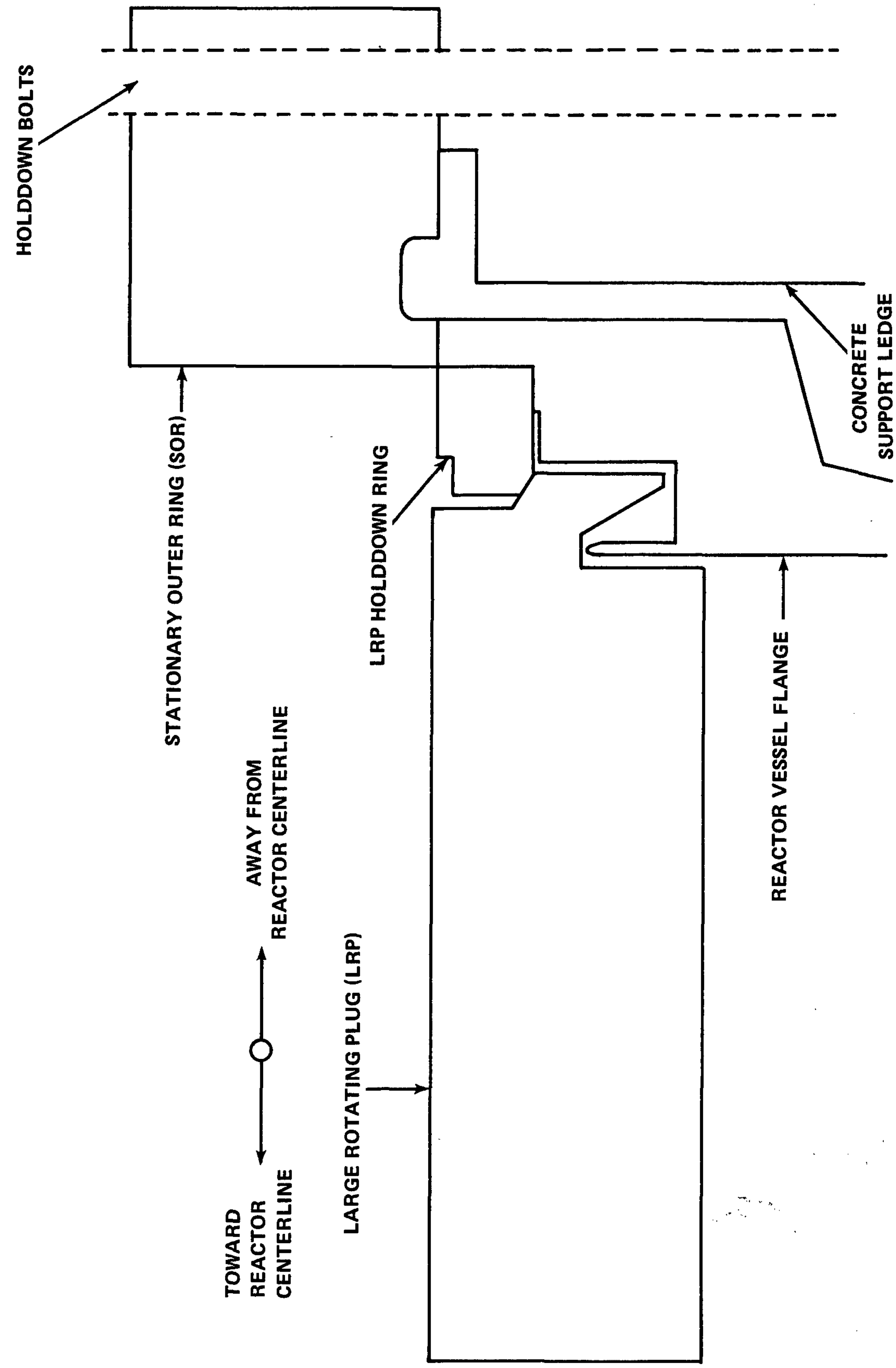


FIG. A–19 LRP HOLD DOWN RING CONCEPT

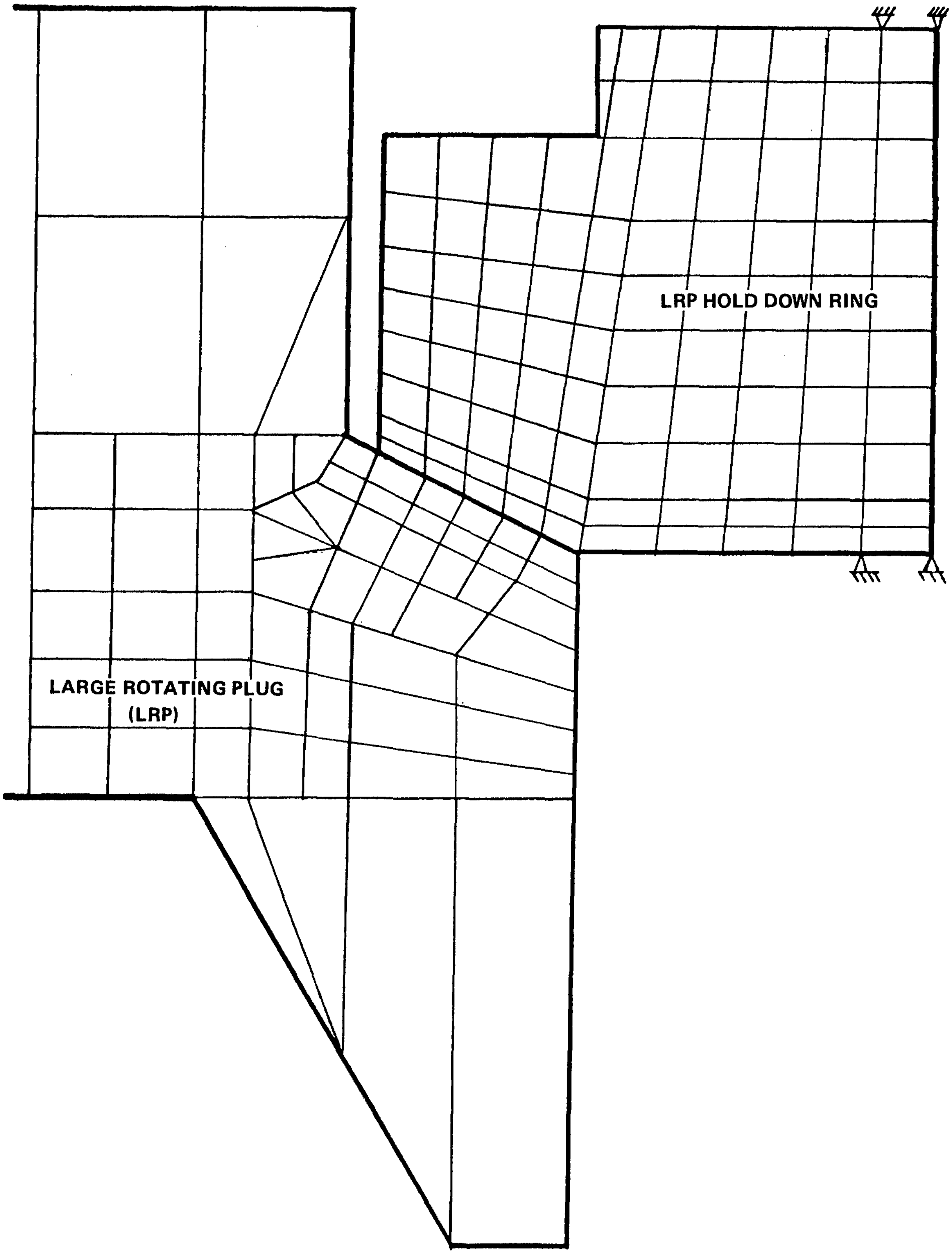


FIG. A - 20 NONSAP LRP HOLD DOWN RING COMPUTER MODEL

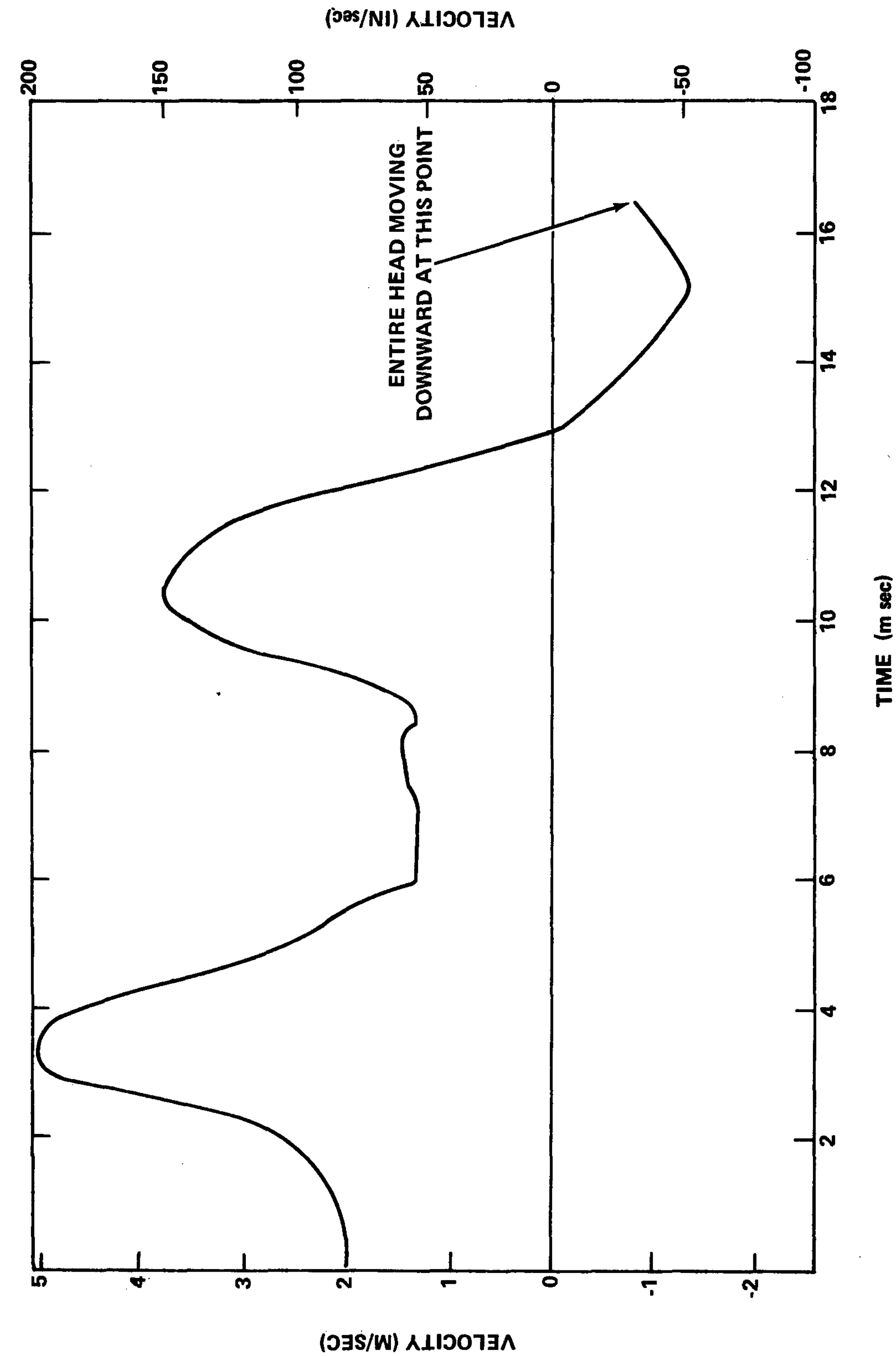


FIG. A - 21 VELOCITY AT CENTER OF REACTOR VESSEL HEAD

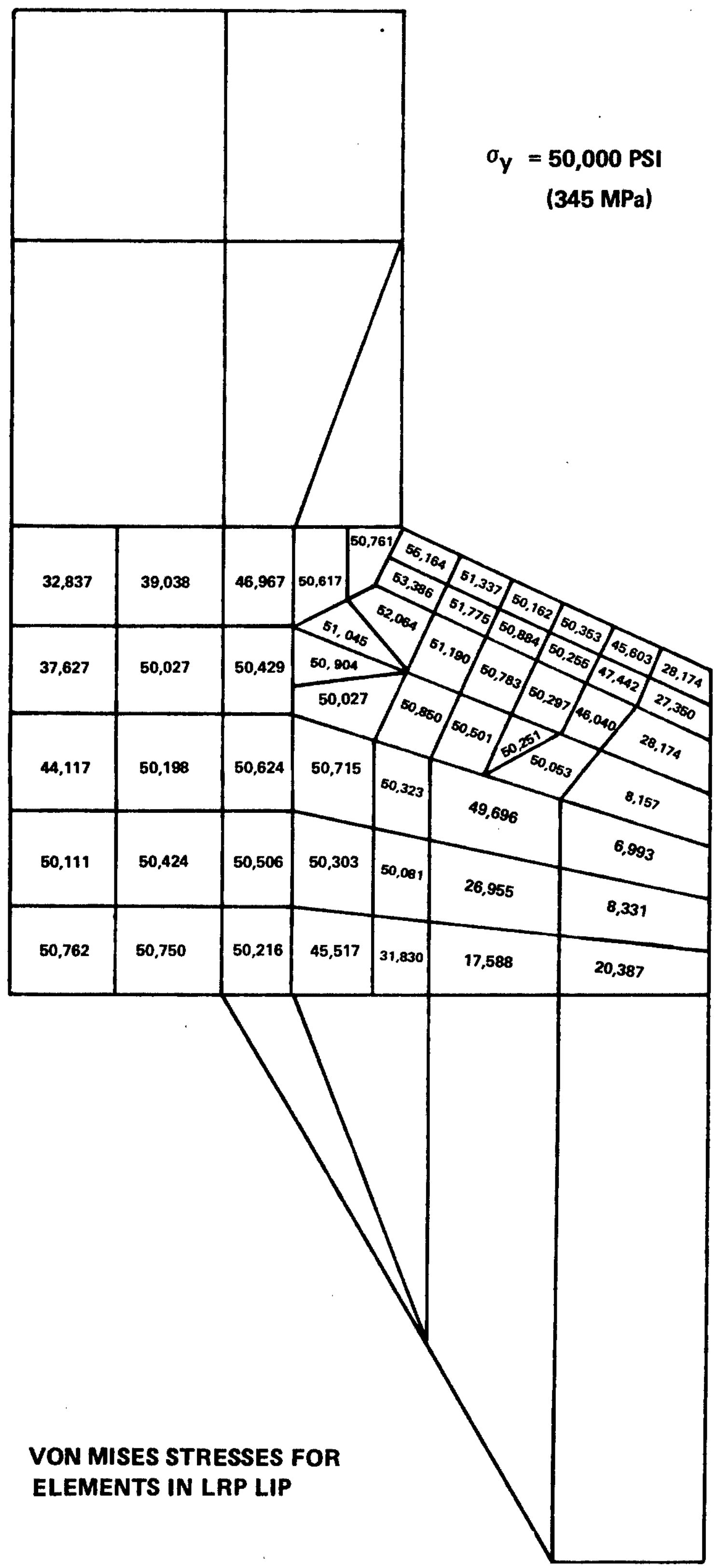


FIG. A - 22 VON MISES STRESSES FOR ELEMENTS IN LRP LIP

σ_y = 90,000 PSI
(621 MPa)

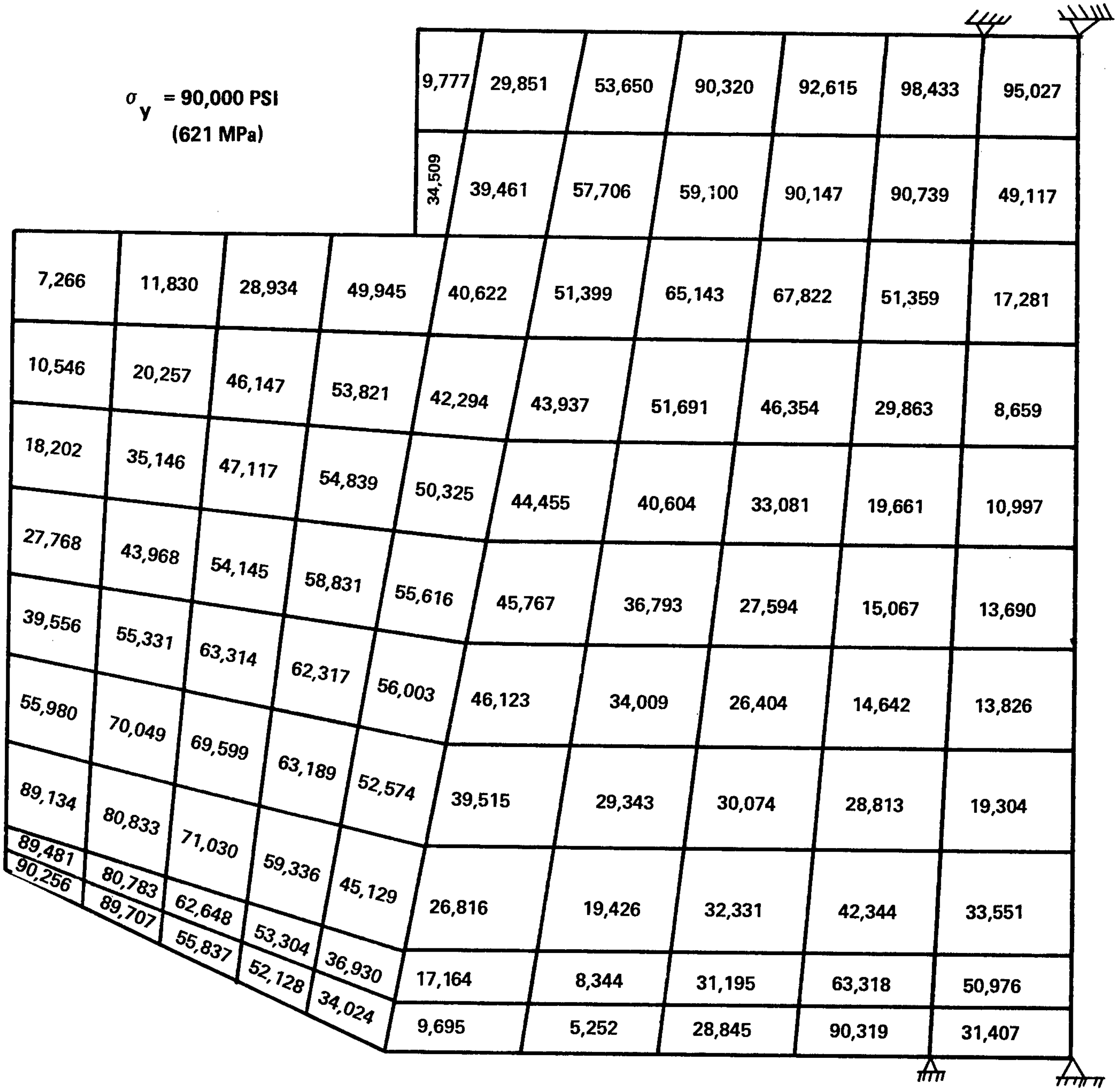


FIG. A-23 VON MISES STRESSES FOR ELEMENTS IN LRP HOLD DOWN RING

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